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F-111 POSITIONAL ERROR ANALYSIS WHEN MOUNTED ON 3 AXIS POSITION--ETC(U)

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In-House Report
October 1977

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F-111 POSITIONAL ERROR ANALYSIS WHEN MOUNTED ON 3 AXIS POSITIONER AT RADC NEWPORT TEST ANNEX

William J. Bocchi

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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This report describes the procedures that were used to determine the true orientation of the F-111 aircraft mounted on the Scientific-Atlanta, Inc. three-axis positioner, model PAEA-85. The report describes the following aspects of this effort: (1) Establishment of the reference coordinate system for the aircraft and alignment of aircraft on pedestal, (2) Development of an inclinometer measurement system for determining aircraft orientation and for estimating errors associated with the aircraft positioning system, (3) Test program for evaluating probable errors in the positioner system, (4) Discussion of results

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of measurements and evaluation of probable system errors, and (5) Recommendations of procedures to be followed for aircraft alignment and for estimating probable system orientation errors.

PREFACE

This report describes the efforts performed to determine the angular positional error associated with supporting an F-111 aircraft on the PAEA-85 three-axis positioner located at RADC's Newport Antenna Test Annex. The work was accomplished under Job Order Numbers 56160101, 21140001 and the Post-Doctoral Program for the Air Force Systems Command. The authors wish to extend their appreciation to Mr. Lawrence Crouth, Captain Willard Haverland, and Sgt William Hendrickson of RADC's Sensor Calibration and Instrumentation Branch for their assistance in this effort. This work was performed during the time period of March 1975 through December 1976. Project Engineer for Job Order Number 56160101 is Mr. Charles A. Lupica, Jr., and for 21140001, Mr. Robert McGregor. Dr. Perkins is a professor of Mechanical Engineering in the Department of Mechanical and Aerospace Engineering of Syracuse University, Syracuse, New York.

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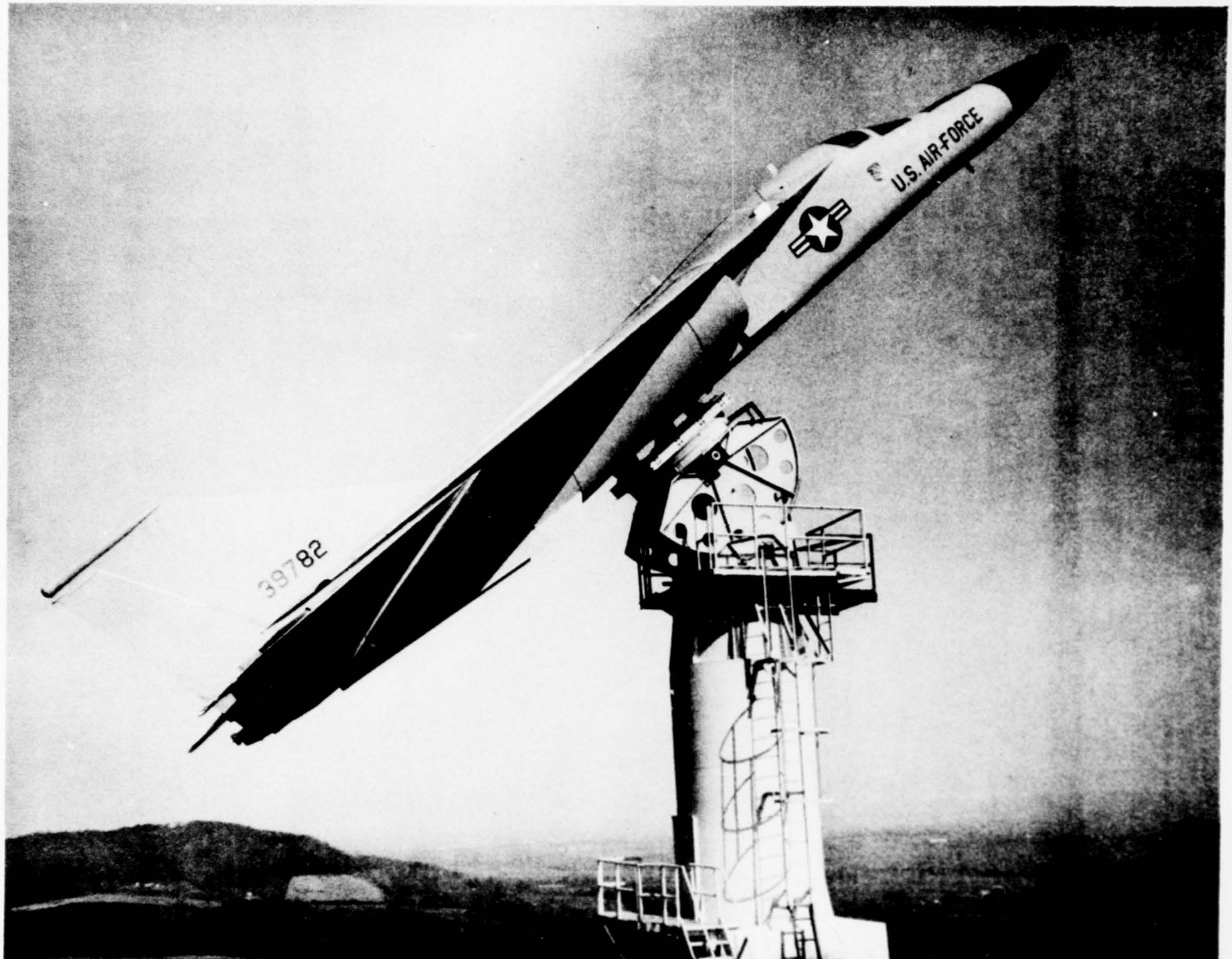
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I. INTRODUCTION

In order to effectively and efficiently evaluate the multiple antenna systems of the F-111 aircraft under realistic flight conditions without actually having to fly the aircraft, an F-111 aircraft was attached to the turntable of a three-axis positioner which is located on top of a 30-foot tower at RADC's Newport Test Annex. The positioner, a Scientific-Atlanta Model PAEA-85, is a three-axis unit, azimuth over elevation over azimuth that allows the aircraft to be tilted in pitch or roll and rotated about its yaw axis. See frontispiece.

The purpose of this effort was to investigate the angular positional error associated with mounting the aircraft to the positioner, and maneuvering the aircraft about its pitch, roll, and yaw axes. This was accomplished by the following: (1) Establishing a coordinate system for the aircraft and alignment of the aircraft on the positioner, (2) Developing an inclinometer measurement system for determing aircraft orientation and for estimating errors associated with the aircraft positioning system, and (3) Testing to evaluate probable errors in the positioner system. Included in this report is a discussion of the results of the measurements, evaluation of system errors, and recommendations of procedures to be followed for aircraft alignment and for estimating system errors.

The results of the test program show that in performing an aircraft rotation about the positioner elevation axis, the error is less than 0.06 degrees. Error is defined as the difference between the positioner turntable movement and the aircraft movement as measured by an inclinometer attached to the aircraft.

II ESTABLISHMENT OF REFERENCE COORDINATE SYSTEM FOR AIRCRAFT AND ALIGNMENT OF AIRCRAFT ON PEDESTAL

After the aircraft was assembled in the hangar, it was leveled following the leveling procedure described in the F-111 maintenance manual. A reference platform was manufactured and installed in the interior of the aircraft at the location designated by the manufacturer for level measurement. The platform was designed to be used with a bubble-type level or with electrical inclinometers such as those manufactured by Schaevitz which were used in this study.

After the aircraft was leveled in the hangar, a system of reference marks were placed on the aircraft fuselage. A system of marks were placed on both sides of the aircraft with the help of an engineer's level. This established a horizontal reference plane. Another set of marks were placed on the top and bottom of the fuselage to define a vertical reference plane. Fore to aft position can be adequately specified in terms of the fuselage station numbers as provided by the aircraft manufacturer's drawings. The details of the procedure which was followed to determine the reference marks are described in Appendix A.

Prior to mounting the aircraft on the pedestal, a test was performed to determine the degree of levelness of the upper and lower turntables. A bench-type level was placed on the pedestal platform and readings were made as the platform was rotated about the lower and subsequently the upper azimuth axes. The test showed that the platform surface was always within 0.01 degrees of level.

After the aircraft was mounted on the table, a surveying test was performed to check the accuracy of the lower azimuth synchro. The synchro

readout was found to be 0.03 degrees different from the value determined by the survey. The procedure is described in Appendix A.

The level of the aircraft after mounting on the pedestal was checked by using the engineer's level situated on a 37-foot Bilby tower. The procedure which was employed is described in Appendix A. During this series of measurements, it was observed that the horizontal reference marks did not all lie in the same plane. Rather, the nose and tail reference marks were observed to lie approximately 5mm lower than the center point of the aircraft.

This aircraft deflection presumably is a result of gravity loading. When the aircraft was leveled in the hangar, the aircraft was supported at four jack points on the aircraft. On the pedestal, however, the aircraft is supported at only the mount location with central line at about fuselage station 519. The maximum amount of angular deviation between a point on the fuselage and the pedestal platform can be estimated by considering the aircraft fuselage as a cantilever beam subjected to a uniform load per unit length. For a cantilver beam subjected to a uniform load, the maximum slope of the beam occurs at the free end. Knowing the length of the beam and having the measured value of the tip deflection, the slope can be calculated from the formula $\theta = (4/3)(\delta/\ell)$ where θ represents the slope in radians, δ represents the tip deflection, and ℓ represents the length of the beam. In the case of the aircraft, δ was observed to be 0.1968 inches and ℓ can be taken as 500 inches. For this case, θ can be estimated to be 0.03 degrees. This would represent an estimate of the largest expected difference between the platform slope and the slope at some other point on the fuselage due to deflection of the fuselage.

III INCLINOMETER MEASUREMENT SYSTEM

The turntable position is determined by synchros that measure the elevation and azimuth movements of the turntable and display these movements on digital readouts located at the positioner control console. In order to provide some means for checking the synchro readout system and for estimating the errors associated with aircraft, mount, and pedestal deflection, the aircraft was instrumented with two Schaevitz servo inclinometers. Both inclinometers were mounted on specially made platforms which were attached to the aircraft at the location designated by the manufacturer for measuring the level of the aircraft. One inclinometer was mounted so that its inclination would sense the pitch of the aircraft. The pitch inclinometer was located in the forward fuselage section in the bomb bay area. The other inclinometer was mounted in the wing box area and aligned so that it would sense the roll of the aircraft.

At the time the inclinometers were installed in the aircraft, it was intended only to measure pitch for a nose or tail down elevation maneuver, and to measure roll for a wing down elevation maneuver. Later on in the test program, it was determined that a check of upper azimuth turntable synchro readouts using the outputs of the pitch and roll inclinometers would be worthwhile. Therefore, the mathematical analysis to compute elevation and upper azimuth positions from pitch and roll inclinometer data was performed, data collected, and results obtained. The results showed significant differences between the computed values based on inclinometer data and the positioner synchro readouts. It was then realized that the inclinometers were not mounted at right angles to each other. Thus, the results for the cross-axis tests (where the aircraft is first tilted in elevation, nose

down, then rotated about the upper azimuth axis), and the measurement of roll change during a nose or tail down maneuver, and the measurement of pitch change during a wing down maneuver are affected by the fact that the inclinometers were not aligned at right angles to each other. Preferably, they should have been mounted together at the same location. However, the mathematical analysis and results obtained are presented in the report to show the usefulness of making such tests and to explain the techniques for computing aircraft yaw from pitch and roll data.

The inclinometers are closed-loop, force-balance type sensors. A pendulum mass is suspended which tends to rotate relative to the frame of the inclinometer as the inclinometer is made to tilt. As the pendulum rotates, a signal is generated which drives a torque motor which in turn repositions the pendulum in its null position. The torque motor current is directly proportional to the gravity force acting on the pendulum. Thus, the torque motor and the inclinometer output are directly proportional to the sine of the angle of tilt of the inclinometer base.

The inclinometers used in this study were designed to operate between 0° and $\pm 50^{\circ}$. The instruments were calibrated at the factory at 1° increments throughout its range. The calibrator data as well as other data pertaining to the accuracy of the inclinometer are provided in Appendix B.

When the inclinometer is tilted about its nonsensitive axis, no output voltage would be observed in theory. In practice, however, it is impossible to construct a device which is perfect in this respect. The output which is observed for rotation about the nonsensitive axis is indicated by the instruments cross-axis sensitivity. The numerical value of the cross-axis sensitivity is the measured voltage output which is observed when the inclinometer

is tilted 90 degrees about its nonsensitive axis. Like the primary output of the inclinometer, the voltage output associated with tilt about the nonsensitive axis is proportional to the sine of the angle of tilt.

The analytical procedure which was employed for determining the orientation of the aircraft taking into account both primary and cross-axis sensitivity is described in Appendix C. In Appendix D an analytical procedure for calculating the pitch, roll and yaw rotations associated with inclinometer readings is presented.

IV EXPERIMENTAL TEST PROGRAM FOR EVALUATING SYSTEM POSITIONING ACCURACY

A number of pedestal maneuvers were performed during which time simultaneous measurements of synchro readout and inclinometer voltage were made. Essentially six test maneuvers were performed: (1) Nose-down pitch change, (2) Tail-down pitch change, (3) Right-wing roll change, (4) Left-wing roll change, (5) Level rotation or yaw change, and (6) Cross-axis maneuver consisting of a pitch rotation followed by a 360 degree rotation about the upper azimuth axis.

Measurement data was collected on the dates: 19 September 1975; 6 October 1975; 6 November 1975; 10 December 1975; 19 January 1976; 20 January 1976; and 9 July 1976. All of the above mentioned test maneuvers were performed on 9 July. On the other dates, only pitch or pitch and roll test maneuvers were performed.

A. Pitch Change Tests

The results of the pitch change tests are provided in Tables 1 through 5. The tests were performed by rotating the upper and lower azimuth tables to the desired synchro readout and then by rotating the aircraft about the

elevation axis. Some tests were performed by lowering the nose of the aircraft and others by lowering the tail of the aircraft. With the exception of the first test which was performed on 19 September 1975, the aircraft was oriented so that the pitch inclinometer registered 0.00 degrees after the upper and lower azimuth settings were made. Subsequently the aircraft was oriented to provide the desired pitch as indicated by the pitch inclinometer. Measurements of the synchro readout were made for each pitch orientation setting. For tests performed on 6 November, 10 December, 19 January, 20 January, and 9 July, measurements were also made of the roll orientation as indicated by the roll inclinometer for each pitch orientation of the aircraft.

The tables show the initial synchro and inclinometer readings in degrees. They also show the change in reading for synchro or inclinometer following each orientation change and the difference in degrees between the synchro or inclinometer changes. For the measurements made on 6 November and thereafter, the same kind of data are provided for the roll inclinometers.

Although for some of the data it appears that the difference between inclinometer change and synchro change as the aircraft is tilted about the positioner elevation axis increases with aircraft pitch, the data is not entirely consistent. The largest difference was measured on 19 January 1976 when the aircraft moved 30 degrees for a turntable movement of 28.82 degrees giving a difference of 1.18 degrees. This difference is much larger than the other data. Also, the initial synchro readout for a level inclinometer indication changed greatly between 10 December 1975 and 20 January 1976. See Table 4. However, when this data was collected, the aircraft and instrumentation had experienced severe cold temperatures and very high wind loads (90 mph winds). In addition, an electrical problem involving the cables leading

from the inclinometers to the positioner control console was later discovered. Although this data is included in the report, the most reliable data was that collected on 6 October 1975, 6 November 1975 and 9 July 1976 when the electrical performance of the inclinometers was not in question. These data show that the largest difference would be expected to be less than 0.1 degree. The observed error is shown graphically in Figure 1.

The roll change data collected on 6 November and later seems to show that the aircraft exhibited a slight tendency to roll as the pitch was changed. Roll changes of 0.61 degrees were recorded for a 45 degree pitch change on 20 January. The 6 November data shows only about 0.3 degree roll for 45 degrees pitch whereas the 9 July data shows about 0.2 degree roll for a 30 degree pitch change. This effect is shown graphically in Figure 2. However, the roll change shown is primarly due to misalignment of the inclinometers about the yaw axis. Unfortunately, without a precise alignment of the inclinometers about the yaw axis, the true roll change during a pitch maneuver is not known. This type of test, however, would be useful for determining a misalignment of the fuselage axis of the aircraft with the positioner elevation axis.

B. Roll Change Tests

The results of tests which change the roll orientation of the aircraft are presented in Tables 6 through 9. These tests were performed according to a procedure analogous to that employed in the pitch orientation tests which is described above. The specifics of the aircraft orientation during test are given in the tables. Refer to Figure 3 for a graphical display of the error.

For the tests performed on 19 September and 6 October, the pitch change was not measured as the aircraft was made to roll. Pitch change data

was recorded for the subsequent roll tests on 6 November and 9 July.

The data shows that a small but measurable difference in aircraft roll orientation was observed between the synchro and inclinometer devices. That data collected on 19 September and 6 November seems to indicate a tendency for the difference to increase with the magnitude of the roll angle. This behavior would be expected if aircraft or pedestal deflections were the cause of the measured differences. The data collected on 6 October shows no consistent trend. This data may not be as reliable as the other data owing to the presence of rather large winds (approximately 30 mph) which were blowing on 6 October. The 9 July data, however, also does not seem to show the presence of any consistent trend. Therefore, it does not seem justifiable to conclude that any consistent deflection error was observed for roll orientation.

The result is quite different in the case of the observed changes in pitch orientation which were measured during the roll tests performed on 6 November and 9 July. The results of the 6 November tests show that approximately a 3-degree pitch change accompanies a roll change of 45 degrees. The 9 July data appears to be entirely consistent with the 6 November data and shows that a pitch change of 2 degrees can be expected to accompany a 30-degree roll change. The pitch change which accompanies the roll test is shown graphically in Figure 4. However, the fact that the pitch inclinometer was not perpendicular to the roll inclinometer does not allow the true pitch change to be known. Installing a pitch inclinometer at the same location as the roll inclinometer and precise alignment to insure the sensitive axes of the instruments are at right angles to each other would allow the true pitch movement during a roll maneuver to be known.

Note that in Table 8, pitch change results are performed with no correction for cross-axis sensitivity and with two possible corrections for

cross-axis sensitivity. The ambiguity arises from the fact that the Schaevitz Corporation did not provide information concerning the sign of the inclinometer voltage output when the inclinometer was tilted about its designed non-sensitive axis. For the corrected pitch change, therefore, two values are given, one with the positive choice of sign and one with the negative choice of sign. There is an approximate 0.1 degree difference in the two numbers.

C. Cross-Axis Tests

In this test the nose of the aircraft was depressed 20 degrees below the horizontal followed by a 360 degree rotation of the upper azimuth table. The results of the tests are presented in Table 10A for the aircraft wings in the forward position and in Table 10B for the aircraft wings in the swept back position. Refer to Figures 5 and 6 for a graphical representation of the data. The calculated values of the elevation and upper azimuth rotation were carried out in accordance with the procedure which is described in Appendix D. Although Figures 5 and 6 show maximum azimuth difference on the order of 4 degrees, the previously described misalignment of the inclinometers about a yaw axis is the cause of these large differences. It is interesting to note that the maximum difference between the upper azimuth synchro and the computed upper azimuth orientation is greatest at the 90 and 270 degree orientations. This is when either the left or right wing is straight down, and misalignment of the pitch inclinometer would cause a large error to occur at these orientations. Subsequent observation of the inclinometer installation did reveal the pitch inclinometer to be considerably misaligned with the fuselage centerline axis, although the roll inclinometer was aligned with the aircraft wing box axis. The technique presented, however, is a most powerful one for measuring and computing elevation and upper azimuth errors for a cross-axis maneuver.

Such a test could show positioner and mounting structure flexibility and mechanical positioning error of the upper azimuth system.

Considering the wings-forward condition, the difference between the elevation synchro readout and the calculated value is at the worst, 1.43 degrees when the upper azimuth orientation was 330 degrees. The largest change in elevation is 0.66 degrees since the starting value of elevation was 20.77 degrees when the upper azimuth orientation was zero. The elevation difference appears to be greatest at upper azimuth orientations of 30, 60, 120, 150, 210, 240, 300 and 330 degrees. The smallest difference occurs at the 0, 90, 180, 270, and 360 degree positions.

D. Level Tests

Level tests were performed for rotation about the upper and lower azimuth axes and for aircraft wings in the forward and in the swept back position. All tests were performed on 9 July 1976.

Table 11 shows the results for rotation about the upper azimuth axis with the wings in the forward position. Figure 7 displays this data in graphical form. The turntable was tilted and the elevation synchro indicated -0.81 degrees before commencing the test in order to start with the pitch inclinometer reading initially zero. As the upper azimuth turntable was rotated, the elevation synchro showed a maximum change of 0.04 degrees. The pitch inclinometer indicated a maximum change of 0.26 degrees and the roll inclinometer showed the same change in going from positive 0.17 degrees to negative 0.10 degrees. When the same test was performed with the wings in the swept back position, the pitch and roll changes were approximately one-half of those observed when the wings were in the forward position. It should be noted that initial level was determined using the pitch inclinometer, however,

this does not mean that the turntable was level. The elevation synchro was reset during the test program, after the survey calibration field work had been performed, and the elevation synchro reading for precisely leveling the turntable was not known. Therefore, the inclinometer was used to establish initial level for the turntable. Observation of Figure 7 shows maximum pitch change at an azimuth rotation of 180 degrees and maximum roll change at 90 and 270 degrees. This would be expected with the aircraft level and the turntable tilted for the start of the test. Thus, the amount of aircraft pitch when the turntable is level would be one-half of 0.26 degrees or 0.13 degrees. The amount of aircraft roll when the turntable is level can also be estimated by taking one-half of the difference in roll readings at the turntable 90 and 270 degree positions. This gives a value of 0.135 degrees. The sources of these errors would be due to positioning the aircraft on the turntable (mounting structure inaccuracies), fuselage deflection, and turntable compliance. The fuselage deflection and turntable compliance contribute small errors (see Sections II and V). The majority of the error is due to positioning the aircraft on the turntable. The aircraft is supported on three legs, two front and one aft. Since the aircraft is approximately 0.13 degrees off in both pitch and roll, one of the front legs is most likely a different length than the other two. The leg spacing is approximately 50 inches between the front legs and between the front and rear legs. A difference in length of one leg of 0.11 inches could cause a 0.13 degree error.

The level test which was performed with rotation about the lower azimuth axis indicated extremely small pitch and roll changes. The maximum change was about 0.02 degrees when the wings were in the forward position. A maximum change of only 0.01 degrees was measured when the aircraft wings were in the swept back position.

V DISCUSSION OF RESULTS OF MEASUREMENTS AND EVALUATION OF PROBABLE SYSTEM ERRORS

Errors in the positioning of the aircraft may result from a variety of potential sources. Although it is impossible to determine the true cause of a measured positioning error without ambiguity, certain estimates can be made of the probable magnitude of error associated with certain physical phenomena.

The inclinometer and synchro systems have comparable accuracy. Therefore, consistency of results from the two systems suggests that both are performing accurately. However, when the two measurement systems give different results, it is not possible to ascertain the error of either system. Nonetheless, it seems reasonable to assume that the true error may be approximately proportional to the difference in measured values.

The inclinometer system provides a very useful facility because it is capable of measuring orientation changes that the synchro system cannot measure. For example, the inclinometer system measures the inclination of a certain location on the fuselage of the aircraft whereas the synchro measures the position of the platform of the pedestal. Differences between the two measurements would be expected if the aircraft, the aircraft mount, or the pedestal system exhibit deflections due to the gravitational loading of the entire structure. Furthermore, the inclinometer can measure such orientation changes as a roll change when the aircraft is subjected to a pitch inclination. The synchro system is totally incapable of measuring this kind of aircraft rotation.

For purposes of the present discussion, the following potential sources of error are identified:

Uncertainty in defining a reference coordinate system with respect to the aircraft

Uncertainty in positioning of aircraft on pedestal

Pedestal Deformation:

Gravitational Loading

Wind Loading

Thermal Expansion

Aircraft to Pedestal Mount Structure Deformation:

Gravitational Loading

Wind Loading

Thermal Expansion

Aircraft Deformation:

Gravitational Loading

Wind Loading

Thermal Expansion

Electrical or Mechanical Synchro Readout Error

Human Error

Inaccuracy Due to Misalignment in Upper and Lower Azimuth Tables

Inclinometer Error.

A. Reference Coordinate System

The development of a reference coordinate system for the aircraft is arbitrary. The best that can be done is to devise a rational procedure which could be reproduced by others performing a similar study.

An estimate of the angular error associated with subsequent attempts to perform the same set of steps can be made. When the aircraft was leveled in the hangar, it was estimated that the reference marks would be positioned with an accuracy of ± 0.5mm. Assuming the worst combination of errors, a second attempt to place a system of reference marks could result in an error of 1mm. The angular error is computed by dividing 1mm by the length of the aircraft

fuselage between marks, which is 800 in. x 25.4mm/in. = 20320mm. Thus, the angular error is (1/20320) x 57.3 degrees/radian = 0.003 degrees. The accuracy of the level used to level the aircraft in accordance with the manufacturer's leveling procedure is estimated to be 30 arc seconds per division. A conservative estimate of the accuracy of reading the level is 1/2 a division, or 0.004 degrees.

B. Positioning of Aircraft on Pedestal

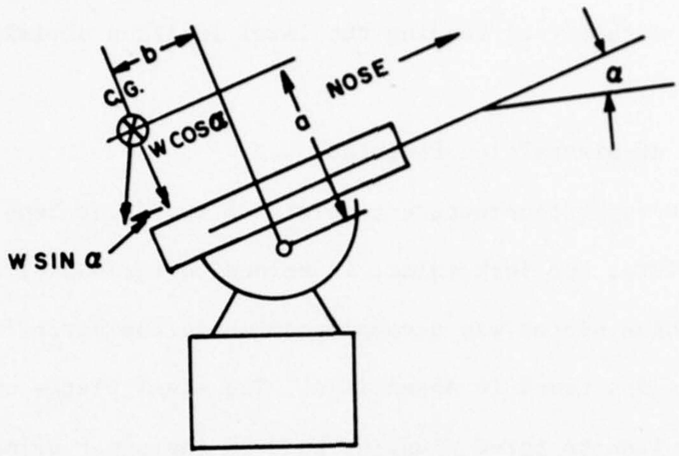
The aircraft support structure consists of two front legs and one rear leg. A steel plate, one inch thick, is welded on the end of each leg. The positioning of these plates was accomplished while the aircraft was in the hangar and leveled as described in Appendix A. The steel plates on the support structure legs are bolted to three mounting pads on the upper azimuth turntable beams. The bolts attaching the aircraft support legs to the mounting pads, and the bolts attaching the mounting pads to the turntable, were tightened with a torque wrench to 100 foot pounds. After the aircraft was attached to the pedestal, final turntable position to level the aircraft in pitch was determined using a precision geodetic level and external targets on the aircraft, as described in Appendix A. In addition, pitch and roll level was verified using the inclinometer within the aircraft. Had significant error been measured, leveling shims could have been placed between the mounting pads and support structure leg plates. The level test, described in Section IV, indicates an error of .13 degrees.

C. Pedestal Deformation

After the pedestal was constructed and installed at the Newport Test Site, Scientific-Atlanta, Inc. performed a number of tests to determine pedestal flexibility and effects of thermal expansion. The results of these

tests can be used to predict the possible errors associated with the use of the F-111 aircraft on the pedestal.

The aircraft center of gravity is located at a variable distance from the elevation axis of the pedestal as shown below:



Refer to Appendix E for a description of the procedure which was employed to determine the location of the center of gravity of the aircraft. The moment M of the aircraft weight with respect to the elevation axis may be expressed as: $M = W \ (a \sin\alpha + b \ \cos\alpha)$. The measured values of W, a, b are: 26, 506 pounds, 92 inches, 39 inches. For a 30 degree tilt, the moment M could be calculated to be 176, 210 foot pounds. In accordance with the results of the Scientific-Atlanta report, the pedestal flexibility with respect to rotation about the elevation axis is 1.41×10^{-9} radians/foot pounds. Thus, for a 30 degree tilt with the tail down, a pedestal platform rotation of 0.14 degrees would be predicted. It would then be expected that the inclinometer and the synchro measurements could differ by as much as 0.14 degrees due to pedestal deflection when the aircraft is tilted 30 degrees.

Pedestal deformation can result from other phenomena such as wind loading or thermal expansion. No information is available concerning the

effects of wind loading, but it is expected that wind effects on the pedestal would be negligible under normal usage situations. The Scientific-Atlanta report provides some data concerning thermal expansion effects. As described on Page 6 of that report, angular changes of the platform amounting to as much as 0.05 degrees have been observed.

D. Aircraft to Pedestal Mount Structure Deformation

It must be expected that mount structure experiences some deformation due to load changes as the aircraft is oriented in different positions. Deformation due to wind loading of the aircraft and thermal expansion effects are possible. At the present time, no information exists as to the magnitudes of these effects, however, it is felt that they should be small in comparison with the corresponding effects for the pedestal.

E. Aircraft Deformation

Some experimental information was obtained concerning the deformation of the aircraft. As described in Section 1 of this report, a maximum slope change of the fuselage centerline due to fuselage flexibility is estimated to be approximately 0.03 degrees.

Some observations were made concerning inclinometer readout fluctuations due to wind loading. On 6 October 1976, while roll measurements were being performed in approximately 20 mph winds, it was observed that the inclinometer readings fluctuated rapidly by as much as 0.02 volts. This is equivalent to approximately a 0.2 degree inclination change. It is not expected that this much flexibility could be exhibited by the aircraft alone, however, it does seem possible that the combined effects of pedestal, mount, and aircraft flexibility could be responsible for inclination changes of this order of magnitude.

Wind loading can result from two primary effects, gusting of wind, and vortex shedding of the fluid as it flows past the aircraft. Gust frequencies would be expected to be on the order of one to several seconds. Vortex shedding frequencies can be estimated from the Strouhel Number S = fd/v where f is the frequency of shedding in hertz; d is some characteristic dimension and v is the wind velocity. For example, taking the dimension d as the fuselage diameter at some point, say 8 feet, for a wind of 20 mph (about 30 fps), the shedding frequency for Strouhel's Number s = 0.2 is:

$$f = \frac{0.2(30)}{8} = 0.75 \text{ hertz}.$$

The shedding frequency for this wind velocity is of the same order of magnitude as the natural frequency of the aircraft, mount, pedestal system. an estimate of the natural frequency of the system was made by exciting the nose of the aircraft in vibration manually for rotation in yaw and in pitch. Measurements of the frequency associated with maximum amplitude of vibration resulted in the natural frequency estimates of 1.3 hertz for yaw vibrations and 2.3 hertz for pitch vibrations. This result suggests that the system is approximately twice as flexible for yaw rotations as it is for pitch rotations. Since the vortex shedding frequencies are of the same order as the system natural frequencies, the observed aircraft oscillations could be due to vortex shedding.

F. Electrical or Mechanical Synchro Readout Error

The accuracy of the synchro system has been observed in the present effort and was previously studied extensively by Scientific-Atlanta, Inc., at the time the pedestal was put into service. The Scientific-Atlanta tests indicate that synchro readouts should always be accurate to 0.01 degree. In the present effort, only the accuracy of the lower azimuth synchro readout was checked. The procedure used is described in Section I and Appendix A of this

report. The measured difference between theodolite measurement and synchro readout was 0.03 degrees for a rotation of about 40 degrees.

The accuracy of the elevation and upper azimuth synchro readouts was not measured, however, the inclinometer test data collected in this report indicates that elevation rotations estimated from synchro or inclinometer measurements are in excellent agreement. Using the most reliable set of measurements which were collected on 9 July 1976 (Tables 5 and 9), it is reasonable to estimate that errors in elevation synchro readout must be less than 0.05 degrees for a rotation of 30 degrees.

G. Human Error

In any system which is man-operated, the possibility exists for human error. These errors may occur as correct instrument readings are incorrectly transcribed or they may occur as a result of incorrect system alignment or setup.

On one occasion during the course of the present study, it was desired to slightly depress the nose of the aircraft and subsequently reset the elevation synchro to read zero. The aircraft nose was raised instead of lowered as a result of incorrectly reading the synchro display. This error was detected from the inclinometer measurements. The tremendous advantage of having a dual measurement system involving both synchro and inclinometer devices is that the possibility of human error is greatly minimized.

H. Inaccuracy Due to Misalignment in Upper and Lower Azimuth Tables Prior to Elevation Rotation

If the upper and lower azimuth tables are misaligned, a positional error can occur. For example, suppose that it is desired to have the aircraft experience a pure pitch or pure roll rotation. The aircraft must first be aligned with its axis either perpendicular to or parallel to the elevation axis of the pedestal. If the axes are not perfectly perpendicular or parallel,

the aircraft will experience a roll rotation when pitch rotation of the aircraft is intended by means of an elevation axis rotation. Similarly, a pitch error will accompany a roll rotation. It will be recalled (Tables 3 and 5 for pitch and Tables 8 and 9 for roll) that some roll change was observed during the pitch tests and a pitch change was observed during the roll tests.

The amount of roll or pitch change which accompanies a given pitch or roll rotation for an assumed misalignment error of the upper and lower aximuth tables can be calculated as follows:

Aircraft is assumed to be rotated a small angle ε about the $\hat{U}_3$-axis (refer to Figure C2 of Appendix C). Subsequently, the aircraft is rotated about the $\hat{U}_2$-axis. (This would be the elevation axis of the positioner.) Rotation about the $\hat{U}_3$-axis is represented by the matrix,

$$A_3 = \begin{bmatrix} \cos\varepsilon & -\sin\varepsilon & 0 \\ \sin\varepsilon & \cos\varepsilon & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Rotation about the $\hat{U}_2$-axis is represented by

$$A_2 = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

After rotation about the $\hat{U}_3$-axis the unit vectors $\hat{U}_1$, $\hat{U}_2$, $\hat{U}_3$ become $\hat{U}_{1'}, \hat{U}_{2'}, \hat{U}_{3'}$.

$$\hat{U}_{1'} = A_3 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad ; \quad \hat{U}_{2'} = A_3 \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

or,

$$\hat{U}_{1'} = (\cos\varepsilon, \sin\varepsilon, 0) \quad ; \quad \hat{U}_{2'} = (-\sin\varepsilon, \cos\varepsilon, 0)$$

After rotation about the $\hat{U}_2$-axis the unit vectors $\hat{U}_1$, $\hat{U}_2$, $\hat{U}_3$ become $\hat{U}_1''$, $\hat{U}_2''$, $\hat{U}_3''$. Thus:

$$\hat{U}_1'' = A_2 \begin{bmatrix} \cos\varepsilon \\ \sin\varepsilon \\ 0 \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\varepsilon \\ \sin\varepsilon \\ 0 \end{bmatrix}$$

$$\hat{U}_2'' = A_2 \begin{bmatrix} -\sin\varepsilon \\ \cos\varepsilon \\ 0 \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} -\sin\varepsilon \\ \cos\varepsilon \\ 0 \end{bmatrix}$$

$$\hat{U}_3'' = A_2 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

Thus:

$$\hat{U}_1'' = (\cos\theta\cos\varepsilon,\ \sin\varepsilon,\ -\sin\theta\cos\varepsilon)$$

$$\hat{U}_2'' = (-\cos\theta\sin\varepsilon,\ \cos\varepsilon,\ \sin\theta\sin\varepsilon)$$

$$\hat{U}_3'' = (\sin\theta,\ 0,\ \cos\theta)$$

Calculating $c_1 = \cos(\hat{U}_1'', -\hat{U}_3)$ and $c_2 = \cos(\hat{U}_2'', -\hat{U}_3)$, we obtain

$c_1 = \sin\theta\cos\varepsilon$ **NOTE: pitch angle = $90 - \cos^{-1} c_1$**

$c_2 = -\sin\theta\sin\varepsilon$ **NOTE: roll angle = $90 - \cos^{-1} c_2$**

For example, suppose $\varepsilon = 1^\circ$, that the upper and lower azimuth tables are misaligned by 1° so that the elevation axis is not aligned with the pitch axis of the aircraft. Therefore, when the elevation axis is rotated, the aircraft will experience a slight roll. If $\theta = 30^\circ$ when $\varepsilon = 1^\circ$, the roll amounts to 0.5°. Figure 2 shows a 0.2° roll change for a 30° pitch change. In the roll tests which were conducted on the pedestal, the aircraft was observed to experience

a pitch change of about 2^{o} for a roll of 30^{o}. See Figure 4. Using the above relations, it will be observed that it would require a misalignment $\varepsilon = 4^{o}$ in order to yeild a pitch change of 2^{o}.

In this case however, the above misalignment is due primarily to inclinometer misalignment rather than misalignment of the turntable. This procedure though can detect the difference between upper azimuth misalignment and deflection of the support structure. Referring to Figures 2 and 4, it will be observed that the pitch and roll changes occur in opposite senses when the direction of rotation is reversed. Thus, if the pitch change is positive when the right wing is tilted down, it is negative when the left wing is tilted down. This behavior is consistent with the predicted result for the case of an initial misalignment error. If aircraft or pedestal deflection were the cause of the pitch change, then either a positive or a negative change for both the left and right wing down rotations would be expected.

A similar error could occur in performing the cross-axis test. The magnitude of this error can be calculated by carrying the preceding analysis one step further. Following the misalignment and the rotation about the elevation axis, the aircraft experiences a yaw rotation with respect to the $\hat{U}_3''$-axis. Denoting the yaw rotation by ψ, the unit vectors $\hat{U}_1'''$, $\hat{U}_2'''$, $\hat{U}_3'''$ are generated by the matrix:

$$A_3'' = \cos\psi \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + (1-\cos\psi) \begin{bmatrix} c_{31}^2 & c_{31}c_{32} & c_{31}c_{33} \\ c_{32}c_{31} & c_{32}^2 & c_{32}c_{33} \\ c_{33}c_{31} & c_{33}c_{32} & c_{33}^2 \end{bmatrix}$$

$$+ \sin\psi \begin{bmatrix} 0 & -c_{33} & c_{32} \\ c_{33} & 0 & -c_{31} \\ -c_{32} & c_{31} & 0 \end{bmatrix}$$

where c_{31}, c_{32}, c_{33} represent the direction cosines of the unit vector $\hat{U}_{3'''}$.

Thus,

$$c_{31} = \sin\theta \quad , \; c_{32} = 0 \quad , \; c_{33} = \cos\theta$$

and,

$$A_3'' = \begin{bmatrix} \cos\psi + (1-\cos\psi)\sin^2\theta & 0 & (1-\cos\psi)\sin\theta\cos\theta \\ \sin\psi\cos\theta & \cos\psi & -\sin\psi\sin\theta \\ (1-\cos\psi)\sin\theta\cos\theta & \sin\psi\sin\theta & \cos\psi + (1-\cos\psi)\cos^2\theta \end{bmatrix}$$

Now,

$$\hat{U}_{1'''} = A_3''\,\hat{U}_{1''} \quad ; \quad \hat{U}_{2'''} = A_3''\,\hat{U}_{2''}$$

The values of $c_1 = (\hat{U}_{1'''} \cdot -\hat{U}_3)$ and $c_2 = (\hat{U}_{2'''} \cdot -\hat{U}_3)$

$$c_1 = -((1-\cos\psi)\sin\theta\cos^2\theta\cos\varepsilon + \sin\psi\sin\theta\sin\varepsilon - (\cos\psi + (1-\cos\psi)\cos^2\theta)\sin\theta\cos\varepsilon)$$

or,

$$c_1 = \sin\theta\cos\psi\cos\varepsilon - \sin\psi\sin\theta\sin\varepsilon = \sin\theta\,(\cos\psi\cos\varepsilon - \sin\psi\sin\varepsilon)$$

$$= \sin\theta\cos(\psi+\varepsilon)$$

$$c_2 = -(-(1-\cos\psi)\sin\theta\cos^2\theta\sin\varepsilon + \sin\psi\sin\theta\cos\varepsilon + (\cos\psi + (1-\cos\psi)\cos^2\theta)\sin\theta\sin\varepsilon)$$

$$c_2 = -\sin\theta\sin\psi\cos\varepsilon - \cos\psi\sin\theta\sin\varepsilon = -\sin\theta\,(\sin\psi\cos\varepsilon + \cos\psi\sin\varepsilon) = -\sin\theta\sin(\psi+\varepsilon)$$

These calculated values of c_1 and c_2 are analogous to those calculated in Appendix D. Note that these expressions differ only by having the upper azimuth rotation angle ψ replaced by the sum of the misalignment angle ε and

the upper azimuth rotation angle ψ. If the misalignment angle ε is zero, the calculations reduce to the same result.

Referring to Figures 5 and 6, note that the synchro and inclinometer differences exhibit a periodic behavior. A misalignment error would be expected to give a constant difference rather than the observed one. It might be suspected that gravitational loading and pedestal flexibility could be responsible for the observed system error behavior. On the other hand, inspection of Tables 10A and 10B show that at a 90-degree upper azimuth rotation, the nose of the aircraft was pointing slightly above level whereas at the 270-degree upper azimuth rotation, the nose was slightly below level. This behavior would be expected to result from a misalignment error. It is interesting to note that the observed difference of four degrees is almost exactly the same as the estimated misalignment error needed to explain a pitch rotation during the roll test. Therefore, the evidence seems to suggest that the observed differences were the result of misalignment error rather than of pedestal or mount deflection. Again, this misalignment error could be due to inclinometer misalignment. In order to accurately measure upper azimuth turntable misalignment, it would be necessary to insure the inclinometers were previously aligned about a yaw axis.

I. Inclinometer Error

Based on the manufacturer's specifications, the hysteresis and resolution of the instruments are less than 0.0001 percent full scale where full scale is defined as from negative full range to positive full range. Full range for these instruments is ± 50 degrees. Therefore, the accuracy of the inclinometers is 0.000001 x 100 or 0.0001 degrees. However, since the inclinometers were not mounted on a motionless surface, the output voltage was not constant.

A digital voltmeter, reading in the millivolt range, was used when collecting the data during calm wind conditions. When the inclinometer readings fluctuated due to the wind moving the aircraft, the hundreths scale of the voltmeter was used. It is estimated that the inclinometer readings were accurate to within 0.005 volts which is equivalent to 0.05 degrees. Also, during one of the tests, the inclinometers were reversed to insure that both instruments gave similar readings.

VI SUMMARY AND CONCLUSIONS

The following data is a summary of the errors described in the previous section:

SUMMARY OF ERRORS

Error Source	Estimated Maximum Magnitude
Establishing Reference Coordinate System	
Placing reference marks on aircraft	0.003 degrees
Leveling aircraft with a spirit level	0.004 degrees
Positioning of Aircraft on Pedestal	0.13 degrees
Pedestal Deformation	
Gravitational Loading	0.14 degrees
Thermal Expansion	0.05 degrees
Aircraft Deformation	0.03 degrees
Electrical or Mechanical Synchro Readout Error	0.05 degrees
Inclinometer Readout Error	0.05 degrees

The total system error can be classified as random error or as systematic error. An example of systematic error is error resulting from aircraft, mount,

or pedestal deflection. This kind of error should be observed to increase as the magnitude of the loading increases. Another example of systematic error is that due to initial misalignment of the upper and lower azimuth tables. By contrast, the cause of random error is unpredictable although the probable magnitude can be estimated from a set of experimental data.

In the present study, estimates of total system error are based on the experimental measurements made with the Schaevitz inclinometers. The evidence which was collected in this study seems to support a number of conclusions although it would be desirable to have a greater amount of data upon which to draw conclusions. The following statements are believed to be true:

1. In performing an aircraft rotation about the elevation axis, the system error is a random error. The magnitude of this error appears to be independent of magnitude of rotation and appears to be less than 0.06 degrees. Refer to Figures 1 and 3.

2. In performing a rotation about the upper azimuth axis with zero turntable tilt, the error appears to be systematic with a maximum magnitude of 0.13 degrees. This error is primarily the result of positioning the aircraft on the turntable. Refer to Figure 7 and Section 4, Level Tests.

3. Relatively large differences were observed between the synchro and inclinometer measurements for pitch during a roll change and during the cross-axis test. It is theorized that these differences result from misalignment error rather than from pedestal deflection. The errors are systematic as shown by Figures 2, 4, 5 and 6. It is believed that this kind of error can largely be removed by ensuring the proper alignment of the inclinometers about a yaw axis.

VII RECOMMENDED ALIGNMENT AND MEASUREMENT PROCEDURES

The following recommendations are made concerning the future use of the Scientific-Atlanta pedestal. The procedures which were followed for the present effort are satisfactory. The recommendations which are presented below should increase the accuracy and reliability of the measurement system:

a. Inclinometers. It is recommended that the inclinometers be calibrated before each installation. The calibration procedure should include rotation about both the sensitive and the non-sensitive axis. A laboratory calibration which would simulate the motion of the cross-axis test (as performed with the aircraft in the present effort), should be performed. The calibration tests should also include a calibration for temperature change. Also, alignment of the inclinometers about a yaw axis should be made, both for calibration and when installed inside the aircraft.

b. Determination of Aircraft Reference Coordinate System. A procedure similar to the one followed in the present effort should be followed (Appendix A), however, the calibrated inclinometers should be installed prior to the installation of the reference marks. The inclinometers should be used to establish the aircraft level.

c. Pedestal. Prior to installation of the aircraft on the pedestal, a suitable plate on which the measurement inclinometers are attached should be mounted on the pedestal platform. Pedestal maneuvers similar to those which are intended in use should be performed. Synchro readouts and inclinometer readings should be made to determine a satisfactory correlation between synchro and inclinometer measurements.

d. Aircraft Installation. A procedure similar to the one followed in the present effort should be adopted (Appendix A). The aircraft should be leveled as accurately as possible using the inclinometers as a level measure. The elevation synchro should be set to read zero when the inclinometers indicate level. The level of the aircraft should be checked with the help of the Bilby Tower and engineer's level (Appendix A). At this time an estimate of aircraft deformation, or tendency of the nose and tail of the aircraft to droop, should be made by measuring the deviation of the level reference marks from the level plane as determined with the engineer's level. The accuracy of the lower azimuth synchro readout should be checked by comparison with the survey instruments (Appendix A). It would be desirable to check the accuracy of the upper azimuth synchro also, however, the procedure which is described in Appendix A would have to be modified in order to make this measurement check.

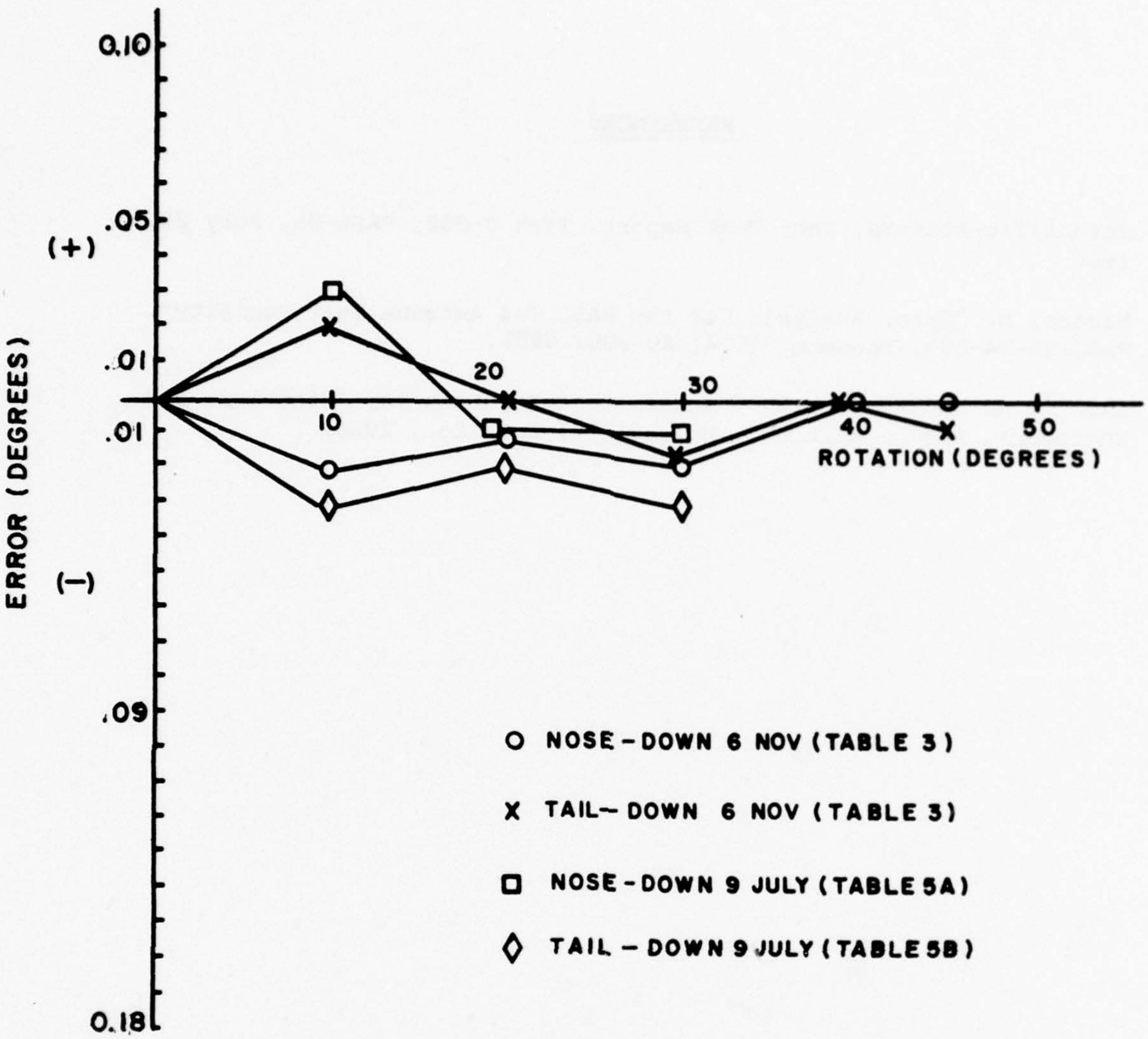
e. System Deformation Characteristics. It is recommended that force-deflection measurements be carried out on the aircraft-mount-pedestal system. Throughout the present effort, it appeared that differences between inclinomete and synchro measurements were to a large degree the result of deformation of parts of the system due to gravitional loading. It is recommended that measurements be performed to determine the deflection contribution of each of aircraft, mount, upper azimuth, elevation and lower azimuth pedestal systems. The procedures which are described in the Scientific-Atlanta report would probably be satisfactory.

REFERENCES

(1) Scientific-Atlanta, Inc. Test Report, Task J-352, PAEA-85, July 29, 1966.

(2) Macera, M. "Error Analysis for the RADC F-4 Antenna Test Facility", RADC-TR-74-309, December 1974, AD B001 090L.

(3) Korn, G.A. and Korn, T.M. "Mathematical Handbook for Scientists and Engineers, Second Edition", McGraw-Hill Book Co., 1968.



Error is defined as the change in synchro readout minus the change in inclinometer measurement, and is expressed in degrees.

Figure 1. OBSERVED ERROR FOR PITCH TEST

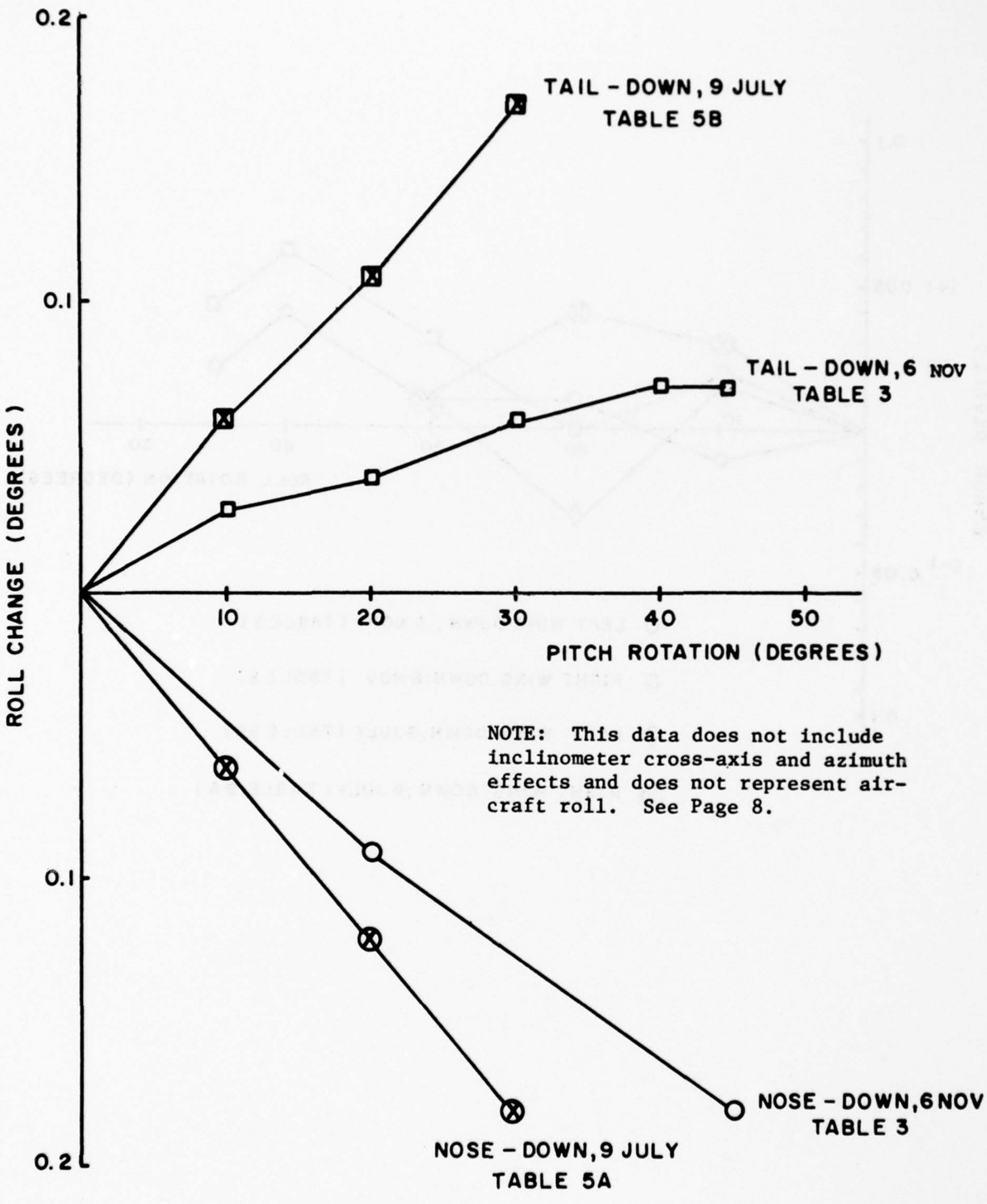


Figure 2. ROLL CHANGE WHICH ACCOMPANY A PITCH ROTATION AS OBSERVED DURING PITCH TESTS

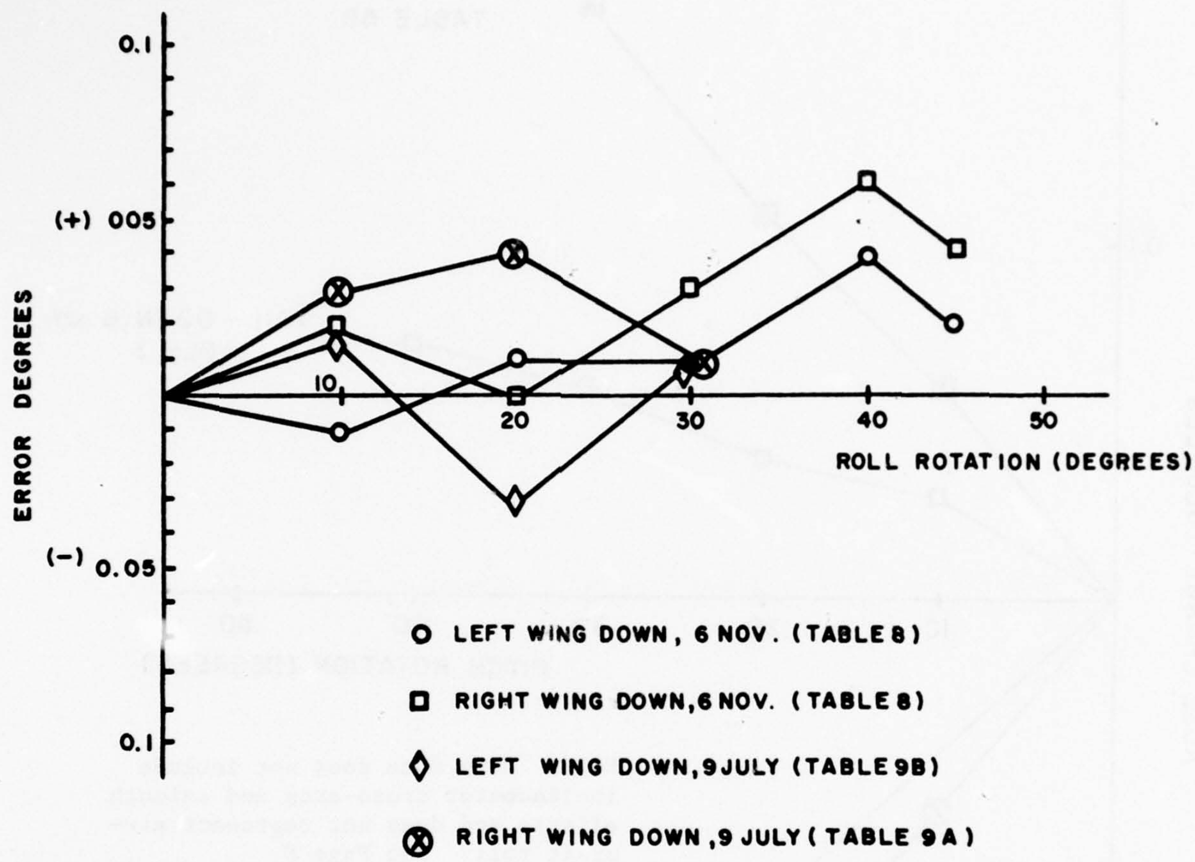


Figure 3. OBSERVED ERROR FOR ROLL TEST

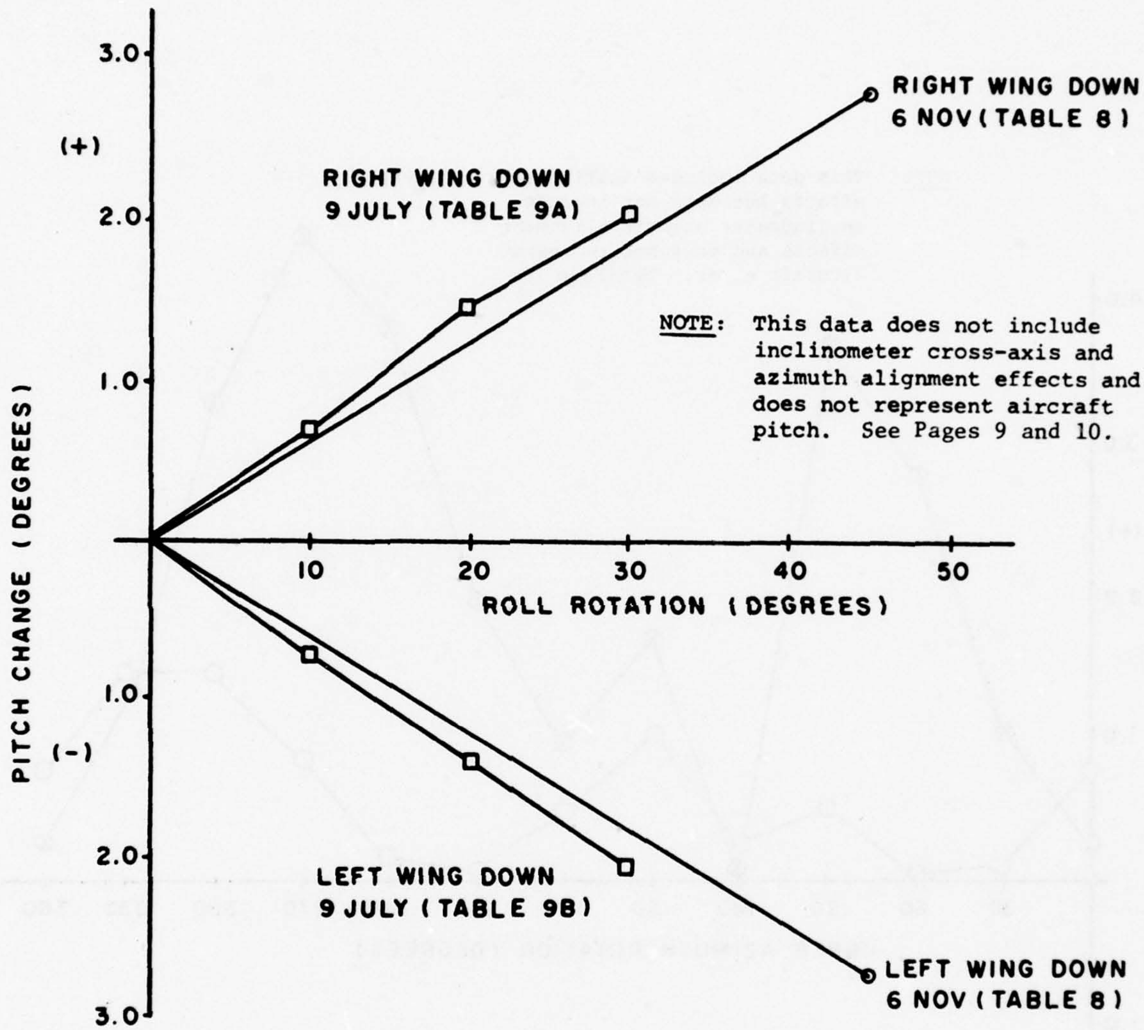


Figure 4. PITCH CHANGES WHICH ACCOMPANY A ROLL ROTATION AS OBSERVED DURING ROLL TESTS

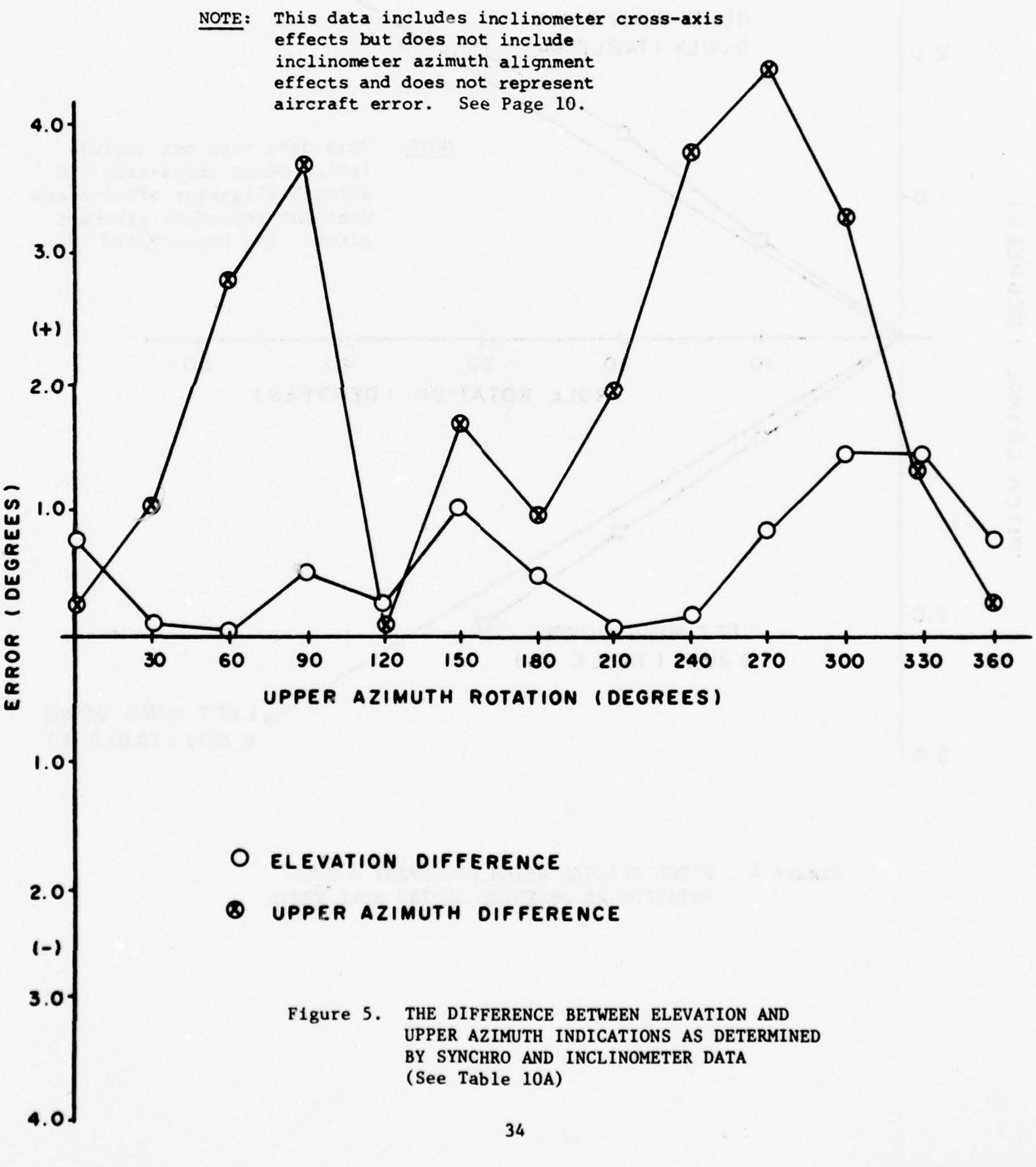


Figure 5. THE DIFFERENCE BETWEEN ELEVATION AND UPPER AZIMUTH INDICATIONS AS DETERMINED BY SYNCHRO AND INCLINOMETER DATA (See Table 10A)

NOTE: This data includes inclinometer cross-axis effects but does not include inclinometer azimuth alignment effects and does not represent aircraft error. See Page 10

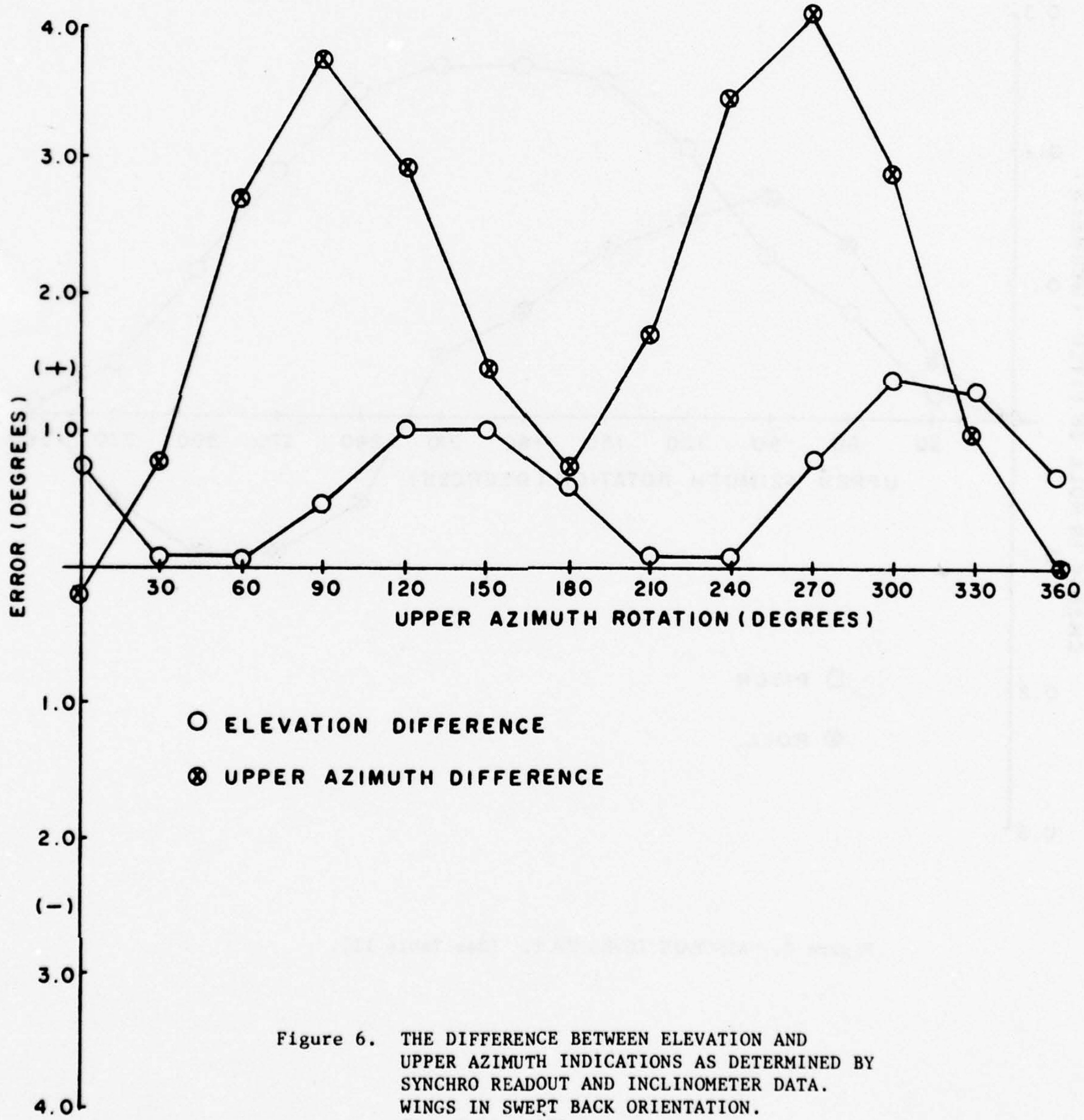


Figure 6. THE DIFFERENCE BETWEEN ELEVATION AND UPPER AZIMUTH INDICATIONS AS DETERMINED BY SYNCHRO READOUT AND INCLINOMETER DATA. WINGS IN SWEPT BACK ORIENTATION. (See Table 10B)

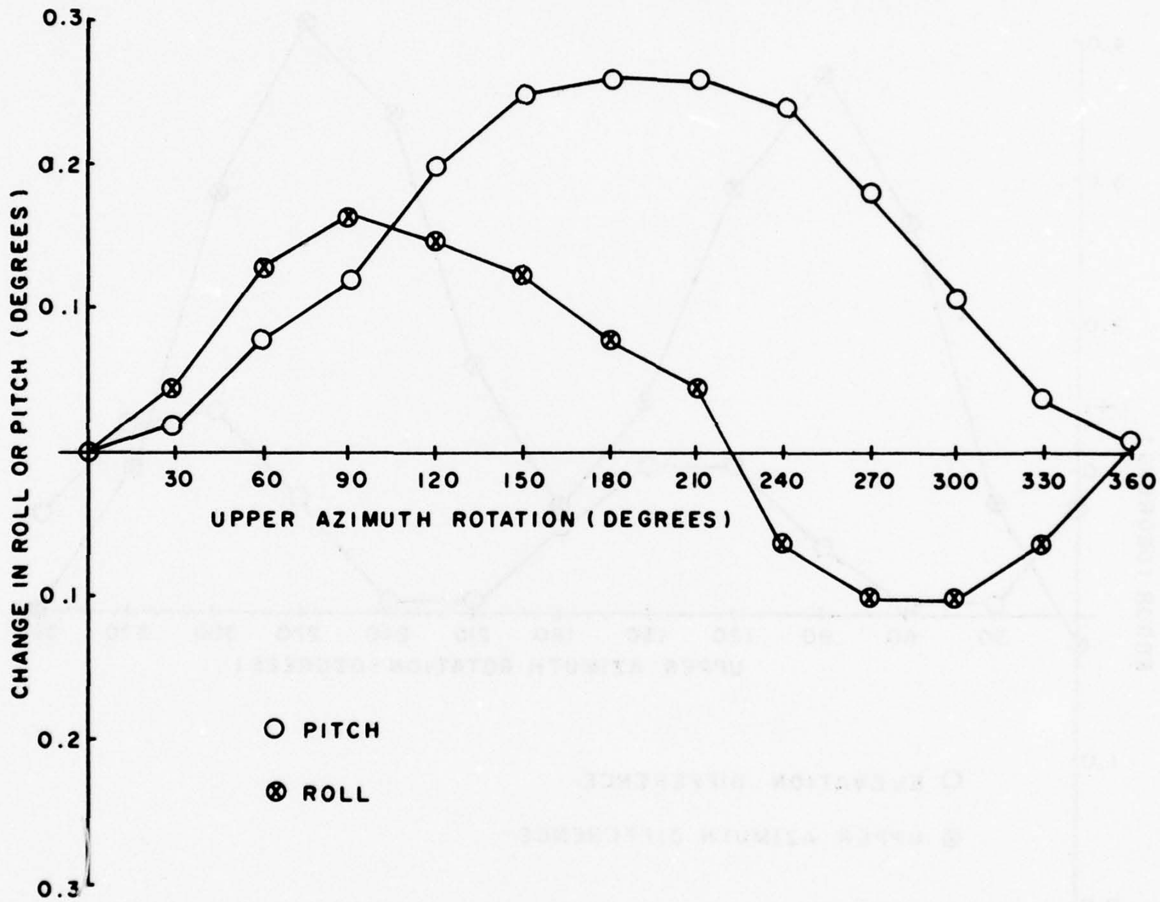


Figure 7. AIRCRAFT LEVEL TEST. (See Table 11).

TABLE 1

Nose Down Pitch
19 September 1975
Data

SYNCHRO READING (deg)	PITCH INCLIN (deg)*	Δsynchro (deg)	Δinclin (deg)	Difference (deg)
0.00	0.62	0.00	0.00	0.00
1.00	1.61	1.00	0.99	-0.01
2.00	2.63	2.00	2.00	+0.01
10.00	10.60	10.00	9.98	-0.02
20.00	21.58	20.00	20.96	+ .96
25.00	25.58	25.00	24.96	- .04
29.46	30.00	29.46	29.38	- .08
34.47	35.00	34.47	34.38	- .09
39.53	40.00	39.53	39.38	- .15
44.52	45.00	44.52	44.38	- .14

*#SN1790

Note: Readout difference appears to gradually increase with the exception of the 20° position. Some indication that pedestal or A/C deflections could be taking place.

TABLE 1A

Tail Down Test
19 September 1975 Data

synchro reading (deg)	Pitch Inclinometer (deg)	Δsynchro (deg)	Δinclin (deg)	Difference (deg)
-0.38	0.00	0.00	0.00	0.00
4.62	5.00	5.00	5.00	0.00
9.62	10.00	10.00	10.00	0.00
14.66	15.00	15.04	15.00	-.04
19.67	20.00	20.05	20.00	-.05
24.68	25.00	25.06	25.00	-.06
29.68	30.00	30.06	30.00	-.06
34.71	35.00	35.09	30.00	-.09
39.71	40.00	40.09	40.00	-.09
44.73	45.00	45.11	45.00	-.11

Notes:

1. Difference increases gradually up to 45 degrees. Pedestal or A/C or mount deflections.
2. Inclinometer was SN1790.

TABLE 2

Pitch Change
6 October 1975 Data

(Est. 20mph winds. Wind caused max. inclin. readout fluctuation of 0.020V or circa 0.2 deg)

SYNCHRO READOUT (deg)	Δsynchro (deg)	Δinclin (deg)	Difference (deg)	
-.58	0.00	0	0.00	Nose down Test SN1790
4.40	4.98	5	-.02	
9.45	10.03	10	.03	
19.44	20.02	20	.02	
29.47	30.05	30	.05	
39.51	40.09	40	.09	
44.54	45.12	45	.12	
-.38	0.00	0	0.00	Tail down Test SN1790
4.59	4.97	5	-.03	
9.66	10.04	10	+.04	
19.64	20.02	20	.02	
29.67	30.05	30	.05	
39.68	40.06	40	.06	
44.71	45.09	45	.09	
-.63	0.00	0	0.00	Nose down Test SN1791
4.36	4.99	5	-.01	
9.39	10.02	10	+.02	
19.41	20.04	20	.04	
29.43	30.06	30	.06	
39.40	40.03	40	.03	
44.39	45.02	45	.02	
-.37	0.00	0	0.00	Tail down Test SN1791
4.62	4.99	5	-.01	
9.74	10.11	10	.11	
19.65	20.02	20	.02	
29.67	30.04	30	.04	
39.60	39.97	40	-.03	
44.54	44.91	45	-.09	

Note: It is tempting to try to see a trend in the difference figures. There appears not to be a consistent trend.

TABLE 3

Pitch Change
6 November 1975
Data

LWAZ 280.06 } pitch
UPAZ 180.00

Wind calm
Pitch Inclin SN1791
Roll Inclin SN1790

SYNCHRO READOUT (deg)	Δsynchro (deg)	Δinclin (deg)	Difference (deg)	Roll inclin (volts)	a Roll Inclin (deg)	a Δroll (deg)	b Roll inclin (deg)	b Δroll (deg)
-.10	0.00	0	0	0.012	.10	0.00	.10 .10	.00 .00
9.88	9.98	10	-.02	-	-	-		
19.89	19.99	20	-.01	0.002	.01	-.09		
29.88	29.98	30	-.02	-	-	-		
39.90	40.00	40	0.00	-	-	-		
44.90	45.00	45	0.00	-.008	-0.08	-.18	-.22 +.06	-.32 -.04
+.18	0.00	0	0.00	+.017	.14	.00	.14 .14	.00 .00
10.20	10.02	10	.02	.020	.17	.03		
20.18	20.00	20	0.00	.022	.18	.04		
30.16	29.98	30	-.02	.024	.20	.06		
40.18	40.00	40	0.00	.025	.21	.07		
45.17	44.99	45	-.01	.025	.21	.07	.35 .07	+.21 -.07

Nose down Test

Tail down Test

Notes:

1. For calculating roll $V_2 - 0.0001 = 6.512c_2$ $c_2 = -\sin$
For calculating pitch in roll test $V_1 + 0.001 = 6.524c_1$ $c_1 = \sin$

2. In columns noted "a" no correction for cross-axis sensitivity was made. In columns noted "b" correction is made. Upper number corresponds to one sign choice while lower number corresponds to other choice. Upper choice was for equation used in cross-axis.

TABLE 4

Pitch Change
10 December, 19 January, 20 January 1976 Data

SYNCHRO READOUT (deg)	Δsynchro (deg)	Δinclin (deg)	Difference (deg)	Roll inclin (deg)	Δroll (deg)
0.23	0.00	0.00	0.00	0.05	0.00
10.25	10.02	10	+.02		
20.22	19.99	20	-.01		
30.19	29.96	30	-.04		
40.21	39.98	40	-.02		
45.19	44.96	45	-.04	0.27	0.22
-.77	0.00	0.00	0.00	-.13	0.00
9.23	10.00	10	0.00		
19.10	19.87	20	-.13		
29.07	29.84	30	-.16		
39.09	39.86	40	-.14		
44.23	45.00	45	0.00	+.48	+.61
-.28	0.00	0.00	0.00		
28.54	28.82	30	-1.18		
43.60	43.88	45	-1.12		

First group (rows 0.23 – 45.19):
10 December 1976
36°F
UPAZ 0.05
LWAZ 0.00

Second group (rows -.77 – 44.23):
20 January 1976
26°F
UPAZ 359.95
LWAZ 0.00

Third group (rows -.28 – 43.60):
19 January 1976

Table 5A

Nose Down Test for
A/C Pitch
9 July 1976 Data

SYNCHRO READING (deg)	INCLINOMETER-PITCH (deg)	ΔSYNCHRO	ΔINCLIN	DIFFERENCE	ROLL INCLINOMETER (deg)	ΔROLL (deg)	
-.80	0.00	0.00	0.00	0	+0.09	0.00	Left Wing Down
9.23	10.00	10.03	10.00	+.03	+0.03	-0.06	Left Wing Down
19.19	20.00	19.99	20.00	-.01	-0.03	-0.12	Right Wing Down
29.19	30.00	29.99	30.00	-.01	-0.09	-0.18	Right Wing Down

Notes:

1. Pitch difference does not consistently change with pitch, thus it appears that pedestal or A/C deflection is not a factor for this test for pitch angles up to 30 degrees.
2. Roll variation totals about 0.2 degrees for a 30-degree change in pitch. This measurement shows power of system since without the two inclinometers, no measure of this kind could be carried out. No correction for cross-axis sensitivity was made.

Table 5B

Tail Down Test for
A/C Pitch
9 July 1976 Data
Up Az 180.05 degrees

PITCH SYNCHRO (deg)	INCLIN-PITCH (deg)	Δsynchro	Δinclin	Difference	Roll inclin (deg)	Δroll (deg)	
-.48	0	0.00	0.00	0.00	+.18	0.00	Left wing down
9.49	10.00	9.97	10.00	-.03	.24	+0.06	Left wing down
19.50	20.00	19.98	20.00	-.02	.29	+0.11	Left wing down
29.49	30.00	29.97	30.00	-.03	.35	+0.17	Left wing down

Notes:

1. Rotation about up az to 180.05 degrees seems to accentuate left-wing down attitude. In contrast to nose-down test with up az at 0.05 degrees the roll is such as to increase left-wing down attitude in this test. Looking at this as a pedestal error we expect this behavior due to az difference of 180 degrees. Thus, both nose-down and tail-down test result in a roll rotation of the same sense to an observer fixed with the ground (as opposed to fixed with the up-az-table.)
2. In both the nose-down and tail-down tests, the difference between change in synchro and change in inclinometer is ve[illegible]all, being less than or equal to 0.03 degrees. No consistent [illegible]nd can be observed.

TABLE 6

Roll Test
Left Wing Down
Right Wing Down
<u>19 September 1975 Data</u>
LWAZ 280.06
UPAZ 180.00

SYNCHRO (deg)	Inclin (deg)	Δsynchro (deg)	Δinclin (deg)	Difference (deg)	
-.61	0.00	0.00	0.00	0.00	Left Wing Down
9.36	10.00	9.97	10.00	+.03	
14.36	75.00	14.97	15.00	+.03	
19.35	20.00	19.96	20.00	+.04	
29.32	30.00	29.93	30.00	+.07	
39.27	40.00	39.88	40.00	+.12	
44.26	45.00	44.87	45.00	+.13	
-.33	0.00	0.00	0.00	0.00	Right Wing Down
9.65	10.00	9.98	10.00	+.02	
44.58	45.00	44.91	45.00	+.09	

Note: Pedestal, A/C, or mount deflection seems indicated.

TABLE 7

Roll Change
6 October 1975 Data

(Est. 20 mph winds causing max. inclin readout fluctuation of 0.020V or circa 0.2 degrees)

A/C nose, tail, wing pointing toward Tanner Hill.

SYNCHRO READOUT (deg)	Δsynchro (deg)	Δinclin (deg)	Difference	
-.61	0.00	0	0.00	Left Wing Down SN 1791
4.40	5.01	5	+.01	
9.44	10.05	10	.05	
19.42	20.03	20	.03	
29.34	29.95	30	-.05	
39.28	39.89	40	-.11	
44.19	44.80	45	-.20	
				↑ Wind toward Tanner Hill
-.30	0.00	0	0.00	Right Wing Down Sn 1791
4.57	4.87	5	-.13	
9.47	9.77	10	-.23	
19.56	19.96	20	-.04	
29.61	29.91	30	-.09	
39.59	39.89	40	-.11	
44.52	44.82	45	-.18	
-.46	0.00	0	0.00	Left Wing Down Sn 1790
4.43	4.89	5	-.11	
9.48	9.94	10	-.06	
19.62	20.08	20	+.08	
29.39	29.85	30	-.15	
39.52	39.98	40	-.02	
44.56	45.02	45	+.02	
				↓ Wind (~30mph) from Tanner Hill
-.37	0.00	0	0.00	Right Wing Down SN 1790
4.63	5.00	5	0.00	
9.70	10.07	10	.07	
19.59	19.96	20	-.04	
29.65	30.02	30	.02	
39.49	39.86	40	-.14	
44.69	45.06	45	+.06	

TABLE 8

Roll Change
6 November 1975
Data

Wind Calm
PITCH INCLIN
SN1791
ROLL INCLIN
SN1790

SYNCHRO READOUT	Δsynchro (deg)	Δinclin (deg)	Difference (deg)	PITCH inclin (volts)	PITCH inclin (deg) a	ΔPITCH (deg) a	PITCH inclin (deg) b	ΔPITCH (deg) b
.31	0.00	0	0.00	-.017	-.14	.00		.00
10.30	9.99	10	-.01	-.095				
20.32	20.01	20	+.01	-.168				
30.32	30.01	30	.01	-.235				
40.35	40.04	40	.04	-.295	-2.80	-2.66	-2.76 -2.86	-2.62 -2.72
45.33	45.02	45	.02	-.321				
.52	0.00	0	0.00	-.011	-.09	.00	-.09 -.09	.00 .00
10.54	10.02	10	.02	+.068				
20.52	20.00	20	.00	.146				
30.55	30.03	30	.03	.221				
40.58	40.06	40	.06	.289				
45.56	45.04	45	.04	.320	+2.82	+2.91	2.77 2.87	2.86 2.96

Left Wing Down Test
LWAZ 270
UPAZ 270
Nose toward Tanner Hill

Right Wing Down Test
LWAZ 0
UPAZ 90
Nose Toward Isolation Tower

Notes:

1. For calculating roll $V_2 - 0.0001 = 6.512\ c_2$ $\quad c_2 = \sin$. For calculating pitch in roll test $V_1 + 0.0001 = 6.524\ c_1$ $\quad c_1 = \sin$
2. In columns noted "a", no correction for cross-axis sensitivity was made. In columns noted "b", correction is made. Upper number corresponds to one sign choice while lower number corresponds to other choice. Upper choice was for equation used in cross-axis data.

TABLE 9A

Right Wing Down Test
for A/C Roll
9 July 1976 Data

LWAZ 0.00
UPAZ -89.95 (270.05)

ROLL SYNCHRO (deg)	ROLL INCLIN (deg)	Δsynchro	Δinclin	Difference (deg)	Pitch Inclin (deg)	Δpitch (deg)
-.50	0.00	0.00	0.00	0.00	.11[a]	0.00
9.53	10.00	10.03	10.00	+.03	.61[b]	0.72
19.54	20.00	20.04	20.00	+.04	1.33[b]	1.44
29.51	30.00	30.01	30.00	+.01	2.02[b]	2.13

[a] Nose Down
[b] Nose Up

TABLE 9B

Left Wing Down Test
for A/C Roll
9 July 1976 Data

LWAZ 0.00
UPAZ 270.05

ROLL SYNCHRO (deg)	INCLIN ROLL (deg)	Δsynchro	Δinclin	Difference (deg)	Pitch inclin (deg)	Δpitch (deg)
-0.74	0.00	0.00	0.00	0.00	.19	0.00
9.28	10.00	10.02	10.00	+.02	.90	0.71
19.23	20.00	19.97	20.00	-.03	1.58	1.39
29.27	30.00	30.01	30.00	+.01	2.22 nose-down	2.03

TABLE 10A

Cross-Axis Test
9 July 1976 Data

LWAZ 0.00 Wings Forward
UPAZ 0.05
ELEV. 20.00 (nose down)
Rotate UPAZ

UPAZ SYNCHRO	CALCULATED ELEV. (deg)	CALCULATED UPAZ (deg)	ELEV. DIFF (deg)	UPAZ DIFF (deg)	d_1	d_2	c_1	c_2
0.05	20.77	0.28	0.77	0.28	-2.314	-.003	-.355	-.0017
30	20.13	31.04	0.13	1.04	-1.922	-1.149	-.295	-.177
60	20.07	62.82	0.07	2.82	-1.020	-1.984	-.157	-.305
(2) 90	20.55	86.32	0.55	3.68	.150	-2.282	.023	-.350
120	20.32	119.82	0.32	-0.12	1.129	-1.966	0.172	-.301
150	21.02	151.63	1.02	1.63	2.060	-1.117	0.316	-.170
180	20.50	180.96	0.50	-0.96	2.284	.030	0.350	0.003
210	20.04	211.95	.04	1.95	1.895	1.174		
240	20.18	243.80	.18	3.80	.991	2.012		
270	20.84	265.55	.84	4.45	-.183	2.310		
300	21.43	303.32	1.43	3.32	-1.312	1.993		
330	21.43	331.35	1.43	1.35	-2.093	1.148		
360	20.77	.25	.77	.25	-2.313	-.002		
0.05								

See following page for NOTES.

TABLE 10A NOTES:

1. Equations used:

$$V_1 + 0.001 = 6.524c_1 - 0.008c_1 = d_1 \qquad \Delta = 42.484$$

$$V_2 - 0.001 = -0.023c_1 + 6.512c_1 = d_2$$

$$\Delta c_1 = \begin{vmatrix} d_1 & -0.008 \\ d_2 & 6.512 \end{vmatrix} \qquad \Delta c_1 = \begin{vmatrix} 6.524 & d_1 \\ -0.023 & d_2 \end{vmatrix}$$

$$\psi = \tan^{-1}(-c_1/c_1) \qquad \nu = \sin^{-1}\sqrt{c_1^2 + c_1^2} \qquad \psi = \cos^{-1} c_1/\sqrt{c_1^2 + c_1^2}$$

2. Due to very small value of c_1 the calculated value of ψ may be in error. Suppose $c_1 = 0.020$, then $\psi = 86.72$. Suppose $c_1 = 0.015$, then $\psi = -87.55$.

TABLE 10B

Cross-Axis Test
9 July 1976 Data
Wings Swept Back

LWAZ 0.00
UPAZ 0.05
ELEV 20.00
ROTATE UPAZ

UPAZ SYNCHRO	CALCULATED ELEV.	Calculated UPAZ (deg)	ELEV. DIFF. (deg)	UPAZ DIFF. (deg)	d_1	d_2	c_1	c_2
0.05	20.77	-0.20	.77	-.20	-2.314	0.000		
30	20.08	30.81	.08	.81	-1.922	-1.138		
60	20.05	62.78	.05	2.78	-1.021	-1.982		
90	20.52	86.21	.52	-3.79	+.154	-2.278		
120	21.07	123.00	1.07	+3.00	+1.280	-1.968		
150	21.08	151.50	1.08	+1.50	2.064	-1.125		
180	20.60	180.75	.60	.75	2.293	0.022		
210	20.06	211.69	.06	1.69	1.903	1.167		
240	20.14	243.47	.14	3.47	1.001	2.003		
270	20.82	265.87	.82	-4.13	-.170	2.309		
300	21.41	302.96	1.41	+2.96	-1.298	1.999		
330	21.35	331.02	1.35	+1.02	-2.079	1.156		
360	20.69	360.05	.69	.05	-2.305	.006		

TABLE 11

A/C Level Test
9 July 1976 Data

LWAZ 0.00
UPAZ Variable
Wings Forward

UPAZ SYNCHRO (deg)	ELEV. SYNCHRO (deg)	ΔELEV SYNCHRO (deg)	(-) = Nose Down PITCH incl (deg)	ΔPitch inclin (deg)	Roll inclin (deg)	Δroll (deg)
0.05	-.81	0.00	0.00	SAME AS PRECEDING COLUMN	0.10	0.00
30	-.81	0.00	0.02		0.15	0.05
60	-.81	0.00	0.08		0.23	0.13
90	-.81	0.00	0.12		0.27	0.17
120	-.79	+.02	0.20		0.25	0.15
150	-.79	+.02	0.25		0.23	0.13
180	-.78	+.03	0.26		0.18	0.08
210	-.77	+.04	0.26		0.15	0.05
240	-.77	+.04	0.24		0.04	-0.06
270	-.77	+.04	0.18		0.00	-0.10
300	-.77	+.04	0.11		0.00	-0.10
330	-.78	+.03	0.04		0.04	-0.06
0.05	-.78	+.03	0.01		0.10	0.00

→ Right wing toward Tanner Hill (at 90)

→ Left wing toward Tanner Hill (at 270)

Notes:

1. A/C level test with rotation about lw. az. results in virtually perfect stability with essentially no tendency to change pitch. Test commences with some roll angle but there is only a very small tendency to change the roll angle. Same holds for wings in swept back position.
2. The A/C level test with wings in swept back position was similar to the present test except the pitch change was only about one half that above. The same was true for roll.

APPENDIX A

SURVEY CALIBRATION EFFORTS FOR F-111 TESTS

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS ROME AIR DEVELOPMENT CENTER (AFSC)
GRIFFISS AIR FORCE BASE, NEW YORK 13441

RADC (OCSA/2215) 20 Nov 1975

Survey Calibration Efforts for F-111 Tests

RADC (TUGS/W. Bocchi)

1. Reference is made to your letter dated 10 July 1975, subject: "Assistance in Performing Error Analysis for F-111 Tests".

2. The attached project report details the calibration and alignment efforts performed by OCSA.

Earl H Filer

EARLE H. FILER

1 Atch
a/s

Error Analysis for F-111 Tests

Calibration and Alignment Efforts

This project is divided into two parts. Part I is associated with only the airplane, i.e., centerline determination and leveling operations. Part II is associated with the accuracy of the entire system, i.e., the airplane, the support pedestal, and the angle sensing devices (the upper and lower azimuth and the elevation readouts) of the support pedestal.

Part I

During the time the F-111 was in the hangar being prepared for installation on the pedestal at IRISH HILL, it was placed on support jacks and leveled. RADC/OCSA personnel assisted in this operation by monitoring the level checkpoints on the aircraft as designated in the manufacturer's maintenance manual. A 10-inch bench type precision level bubble was used for the level determinations. The aircraft was suspended on four jacks, one under the nose, one under the tail, and one under each wing. When leveling was completed, a row of 5 reference points were marked at the same elevation and at approximately the same location on both sides of the fuselage. The marks were set with a steel center punch and encircled with black stick-on targets. A Wild N-3 precision level was used for these observations.

The vertical plane containing the center line was determined and marked on the top and bottom of the airplane. This was done by inspecting drawings and specifications to find the points which defined the center line and then extending these points to the top and bottom of the airplane. To do this a theodolite was carefully positioned over one of these points and sighted forward to the other point. From this line, other points were established and marked. The center of the vertical fin attached to the forward portion of the tail was one of the designated centerline references used.

Part II

Prior to the airplane being installed on the pedestal at the Newport Test Site, a test was performed to determine if the platform on the top of the pedestal would stay level when (1) the upper azimuth was rotated, and (2) the lower azimuth was rotated. For this test, the same bench type level used for the leveling operation in the hangar was mounted on the platform at right angles to the horizontal axis of the upper azimuth table. The elevation axis was then adjusted until the bubble was nearly level. The bubble was observed first as the upper azimuth table was rotated and then as the lower azimuth table was rotated. In each of the

rotations the bubble did not deviate by more than 1/2 a division on the level. One division on the level is approximately 30 arc seconds. This test demonstrated the stability of the pedestal under a no-load condition.

After the airplane was mounted on the pedestal, three tests were performed to determine the accuracy of the angle sensors. The first test was to align the upper azimuth table. Next, the angle readout of the lower azimuth table was tested for accuracy and finally, the elevation axis was calibrated for zero elevation angle.

The first test was performed as follows:

(1) A target was set up at the vertical axis (center point of rotation) of the lower azimuth table. This was done by aligning the target over the center of the hole in the lower azimuth table.

(2) A target (surveying type) was attached directly to one of the previously established centerline reference points located on top of the aircraft and just behind the canopy. The fin, attached to the front portion of the tail section, was used as the back target.

(3) A theodolite was set up over station IRISH ECC which is approximately 1600 feet west of the radar pedestal.

(4) The telescope of the theodolite was then pointed on the target set on the vertical axis of the lower azimuth table. The airplane was then observed through the telescope. The upper and lower azimuths were adjusted until the two targets on top of the airplane came into precise alignment with the theodolite. The elevation axis was then lowered (nose down) to its maximum depression while observing the targets through the theodolite telescope. Minor adjustments were made to upper and lower azimuth settings such that the targets remained in line throughout the movement. The upper and lower azimuth readings were then recorded. They were 0.05 degrees and 304.30 degrees respectively.

The accuracy evaluation of the lower azimuth readout was performed as follows:

(1) A reference point was established approximately 1340 feet south-southwest of the pedestal. This point was called "IRISH FIELD".

(2) A Wild T-2 theodolite was set up at Station "IRISH ECC" and the angle between the F-111 pedestal and "IRISH FIELD" was observed and recorded to be $57^{\circ}18'50''$.

(3) The angle at IRISH FIELD between IRISH ECC and the F-111 pedestal was observed to be 83°23'52".

(4) Adding these angles and subtracting the sum from 180 degrees gives the angle at the F-111 pedestal of 39°17'18" = (39.288°).

(5) With the theodolite at IRISH FIELD the targets on top of the airplane were lined up. The lower azimuth readout was observed to be 265.32°.

(6) With the theodolite at IRISH ECC the targets on top of the airplane were lined up. The lower azimuth readout was observed to be 304.58°.

(7) Subtracting, the angle was found to be 39.26 degrees or 0.03 degrees different from the concluded angle. This was deemed a satisfactory check of the lower azimuth readout.

Finally, the elevation readout was checked as follows:

(1) A 37-foot Bilby tower (surveying tower) was erected about 100 feet south of the F-111 pedestal.

(2) A Wild N-3 precision geodetic level was set on top of the inner section of the Bilby tower.

(3) The bubble of the N-3 was meticulously leveled.

(4) The airplane was first pointed directly at the level. Then it was rotated horizontally, using the lower azimuth only, 90° clockwise.

(5) The points previously established in a horizontal reference plane along the fuselage of the airplane were observed. Minor adjustments in elevation of the N-3 level were accomplished by means of raising or lowering of the foot screws. A level plane was established which extended through the horizontal wire of the instrument and the nose and tail points. The elevation readout was then observed to be 359.78 degrees.

(6) The airplane was then rotated (using lower azimuth only) approximately 160° (to the limit possible). The reference points on the other side were then observed as in Step 5 above. When the plane was established, the elevation readout was 359.77 degrees, changing to 359.78 degrees occasionally.

(7) The reference points located along the central portion of the aircraft (between the nose and tail points) measured approximately five millimeters above the established level plane. This indicates a slight droop from the center section where the airplane is attached and supported, to the nose and tail sections. The most obvious reason for this condition

is the fact that the level line of reference points were established along the sides of the fuselage while the airplane was leveled and supported by four jacks located at the nose, tail, and under each wing.

Accuracy

(1) Points on the top and sides of the airplane (prior to mounting on pedestal) plus or minus 0.5 millimeter from defined line.

(2) Precision of repeated attempts at lining up the targets on top of the airplane: plus or minus 0.01 degrees.

(3) Accuracy of concluded angle at the F-111 pedestal: plus or minus 15" = plus or minus 0.004 degrees.

APPENDIX B

SCHAEVITZ SERVO INCLINOMETER DATA

DATA ITEM	SN 1790	SN 1791
Power supply voltage	15 volts	15 volts
Power supply current	+10-6 ma	+10-6 ma
Frequency response (-3 db)	48 cps	48 cps
Range	50 degrees	50 degrees
Full range output	±4.990 volts	±4.998 volts
Cross-axis sensitivity	0.023 volts/g	0.008 volts/g
Noise	0.003 volts rms	0.003 volts rms
Linearity	±0.004%	±0.01%
Output impedance	5.23 K ohms	5.23 K ohms
[1] zero offset	0.001 volts	-0.0008 volts
[2] Scale factor temperature coefficient	0.0005%/°F	0.0001%/°F
[3] Null temperature coefficient	0.0%/°F	0.001%/°F
Tilt applied so that connector end is lower causes output voltage to become more	positive	positive

[1] Voltage signal output in perfectly level orientation

[2] Change in output voltage per degree Fahrenheit divided by output voltage

[3] Change in output per degree Fahrenheit divided by full scale output (10 volts)

TABLE B1. Calibration data for Inclinometer SN 1790. Calibration performed by Schaevitz Engineering, Inc., using an optical index table with an accuracy of 10 arc seconds. Calibration performed for temperature 75°±1 .

ANGLE	OUTPUT	ANGLE	OUTPUT	ANGLE	OUTPUT	ANGLE	OUTPUT
1°	-0.113	26°	-2.855	359°	+0.114	334°	+2.857
2	-0.227	27	-2.956	358	+0.228	333	+2.958
3	-0.341	28	-3.057	357	+0.341	332	+3.059
4	-0.454	29	-3.157	356	+0.455	331	+3.159
5	-0.567	30	-3.256	355	+0.569	330	+3.258
6	-0.681	31	-3.354	354	+0.682	329	+3.356
7	-0.794	32	-3.451	353	+0.794	328	+3.453
8	-0.906	33	-3.547	352	+0.907	327	+3.549
9	-1.019	34	-3.641	351	+1.020	326	+3.644
10	-1.130	35	-3.735	350	+1.132	325	+3.737
11	-1.242	36	-3.828	349	+1.244	324	+3.830
12	-1.354	37	-3.919	348	+1.355	323	+3.921
13	-1.465	38	-4.009	347	+1.467	322	+4.012
14	-1.575	39	-4.098	346	+1.577	321	+4.101
15	-1.686	40	-4.186	345	+1.687	320	+4.188
16	-1.795	41	-4.272	344	+1.797	319	+4.275
17	-1.904	42	-4.357	343	+1.906	318	+4.360
18	-2.013	43	-4.440	342	+2.014	317	+4.443
19	-2.120	44	-4.523	341	+2.122	316	+4.526
20	-2.227	45	-4.604	340	+2.229	315	+4.607
21	-2.334	46	-4.684	339	+2.335	314	+4.687
22	-2.440	47	-4.762	338	+2.441	313	+4.765
23	-2.545	48	-4.838	337	+2.546	312	+4.841
24	-2.649	49	-4.914	336	+2.651	311	+4.917
25	-2.752	50	-4.988	335	+2.754	310	+4.991

TABLE B2. Calibration data for Inclinometer SN 1791. Calibration performed by Schaevitz Engineering, Inc., using an optical index table with an accuracy of 10 arc seconds. Calibration performed for temperature 75° ±1 .

ANGLE	OUTPUT	ANGLE	OUTPUT	ANGLE	OUTPUT	ANGLE	OUTPUT
1°	-0.115	26°	-2.860	359°	+0.113	334°	+2.860
2	-0.229	27	-2.962	358	+0.227	333	+2.962
3	-0.343	28	-3.063	357	+0.341	332	+3.064
4	-0.456	29	-3.163	356	+0.455	331	+3.164
5	-0.570	30	-3.262	355	+0.568	330	+3.263
6	-0.683	31	-3.360	354	+0.681	329	+3.361
7	-0.797	32	-3.457	353	+0.795	328	+3.458
8	-0.910	33	-3.553	352	+0.908	327	+3.554
9	-1.022	34	-3.648	351	+1.020	326	+3.649
10	-1.134	35	-3.742	350	+1.132	325	+3.743
11	-1.246	36	-3.834	349	+1.244	324	+3.836
12	-1.357	37	-3.926	348	+1.356	323	+3.928
13	-1.469	38	-4.016	347	+1.467	322	+4.018
14	-1.579	39	-4.105	346	+1.578	321	+4.108
15	-1.690	40	-4.193	345	+1.688	320	+4.195
16	-1.799	41	-4.279	344	+1.798	319	+4.282
17	-1.908	42	-4.364	343	+1.907	318	+4.367
18	-2.017	43	-4.448	342	+2.016	317	+4.451
19	-2.125	44	-4.531	341	+2.124	316	+4.534
20	-2.232	45	-4.612	340	+2.231	315	+4.615
21	-2.339	46	-4.692	339	+2.338	314	+4.695
22	-2.445	47	-4.770	338	+2.444	313	+4.773
23	-2.550	48	-4.847	337	+2.549	312	+4.850
24	-2.654	49	-4.923	336	+2.654	311	+4.926
25	-2.758	50	-4.997	335	+2.757	310	+5.000

APPENDIX C

PROCEDURE TO DETERMINE AIRCRAFT ORIENTATION FROM INCLINOMETER VOLTAGE OUTPUT

The inclinometer is designed to provide a voltage output which is proportional to the component of the gravitational force which is acting in the sensitive direction. Referring to Figure C1, the inclinometer is to rotate by an angle θ about an axis normal to the figure. The direction AA' is the "sensitive" direction of the inclinometer. After the inclinometer has rotated by the amount θ, the component of the weight W which is acting along the sensitive axis is $W\sin\theta$. The inclinometer voltage is proportional to $\sin\theta$.

If the inclinometer is rotated about the axis AA' there is a small voltage output. The sensitivity of the inclinometer to rotation about axis AA' is called the cross-axis sensitivity of the inclinometer. The cross-axis sensitivity is the voltage output which is experimentally measured when the inclinometer is rotated 90 degrees from the horizontal about the axis AA' (the so-called non-sensitive axis).

Referring to Figure C2 let $\hat{U}_{1'}, \hat{U}_{2'}, \hat{U}_{3'}$ be unit vectors pointing along the nose, along the right wing and vertically downward when the aircraft is flying level respectively. Let X, Y, Z be a coordinate system fixed in space. As shown in figure C3, the two aircraft inclinometers are aligned differently with respect to the aircraft coordinate system $(\hat{U}_{1'}, \hat{U}_{2'}, \hat{U}_{3'})$. In Figure C3 the X-axis of the inclinometer is the axis corresponding to line AA' of Figure C1.

Denoting V_1, V_2 as the voltage outputs of the no. 1 and no. 2 inclinometers we can write a general relation

$$V_1 = a_{11}\cos(x_1,Z) - a_{12}\cos(y_1,Z)$$

$$V_2 = -a_{21}\cos(y_2,Z) + a_{22}\cos(x_2,Z)$$

where a_{11}, a_{22} represent the primary sensitivities of the two inclinometers and a_{12}, a_{21} represent the cross-axis sensitivities of the two inclinometers. Making use of the relations between x_1,y_1,z_1 and x_2, y_2,z_2 and denoting

$$c_1 = \cos(\hat{U}_{1'},\hat{k}),$$

$$c_2 = \cos(\hat{U}_{2'},\hat{k}),$$

one can rewrite the relations for the voltages as

$$V_1 = a_{11}c_1 - a_{12}c_2,$$

$$V_2 = a_{21}c_1 + a_{22}c_2.$$

Those relations can be solved for c_1, c_2 as

$$c_1 = \frac{V_1a_{22} + a_{12}V_2}{a_{11}a_{22}+a_{12}a_{21}}$$

$$c_2 = \frac{a_{11}V_2 - a_{21}V_1}{a_{11}a_{22}+a_{12}a_{21}}$$

The appropriate values of a_{11}, a_{22}, a_{12}, a_{21} are obtained from the calibration data provided by Schaevitz with the inclinometers. For this report inclinometer no. 1 has taken as SN 1791 and was the inclinometer used to measure aircraft pitch. Inclinometer No. 2 was taken as SN1790 and was the inclinometer used to measure aircraft roll.

The following procedure was used to determine a_{11}, a_{12}: Suppose for inclinometer no. 1 (SN1791) $c_2=0$ and $c_1=\cos(\hat{U}_{1'},\hat{k}) = \sin 30 = 0.5$. This is depicted by Figure C4(a). In accordance with the calibration data, $3.362 = a_{11}\ 0.5$ or $a_{11} = 6.524$. Also in accordance with the calibration data the cross-axis sensitivity is 0.008, therefore, $a_{12} = 0.008$. The proper sign cannot be obtained with absolute certainty. When the aircraft is made to roll with the right wing down as shown in Figure C4(b) it was observed that the pitch or no. 1 inclinometer experienced a positive voltage change. In the case of the right wing down test $c_2 = \cos(\hat{U}_{2'},\hat{k}) = \cos(90+\theta)$ is less than zero. This suggests that the minus sign should be taken. Thus, it is proposed that

$$V_1 = 6.524\, c_1 - 0.008\, c_2 .$$

Following a similar procedure for the case of the no. 2 inclinometer (SN 1790), it is proposed that

$$V_2 = -0.023 c_1 + 6.512 c_2 .$$

The inclinometers both have an electrical offset which must also be taken in account. For SN 1791 the offset is -0.001 volts while for SN1790 the offset is +0.001 volts. Thus,

$$V_1 + 0.001 = 6.524\, c_1 - 0.008\, c_2$$

$$V_2 - 0.001 = -0.023\, c_1 + 6.512\, c_2 .$$

Solving these equations for c_1, c_2;

$$c_1 = \frac{(V_1+0.001)6.512 + (V_2-0.001)0.008}{42.484}$$

$$c_2 = \frac{(V_2-0.001)6.524 + (V_1+0.001)0.023}{42.484}$$

It should be restated that the signs associated with the cross-axis sensitivity are not absolutely certain due to the fact that the Schaevitz calibration data only provided the magnitude of the cross-axis voltage. A sample calculation was performed for the case of a 20° pitch change followed by a 30° yaw as performed in the cross-axis aircraft orientation test. When the signs were as selected above the calculation yaw and elevation were found to be 30.76° and 20.08°. When the signs were reversed, the calculated values were found to be 30.50° and 19.99°. The uncertainty, therefore, appears to be on the order 0.1 to 0.2 degree.

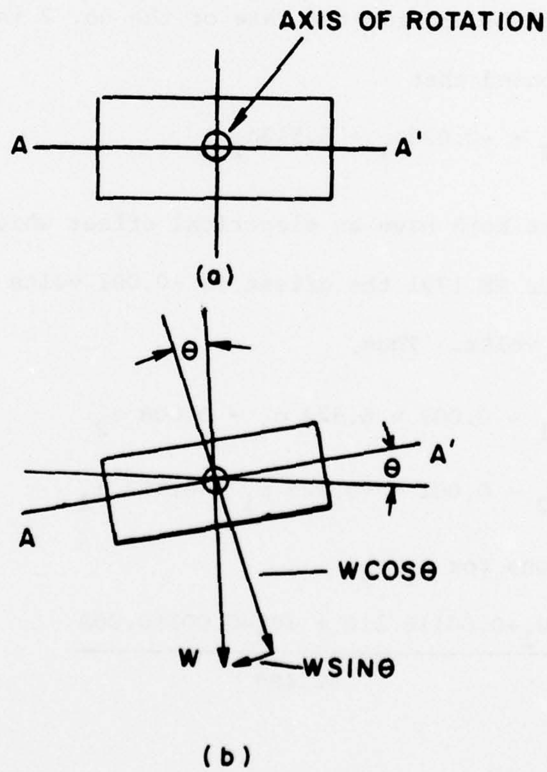


Figure C1. INCLINOMETER OPERATION

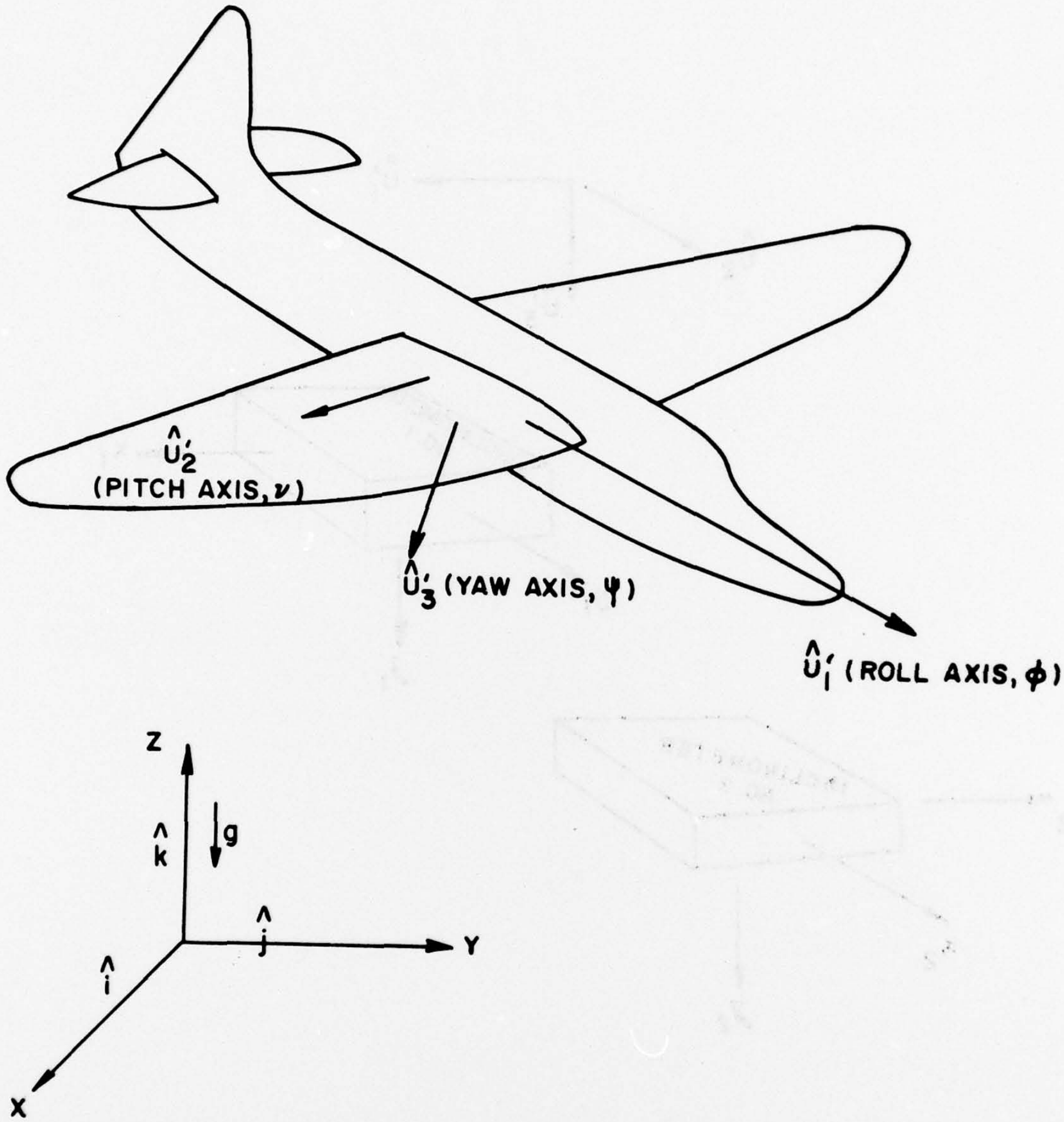


Figure C2. AIRCRAFT COORDINATE SYSTEM

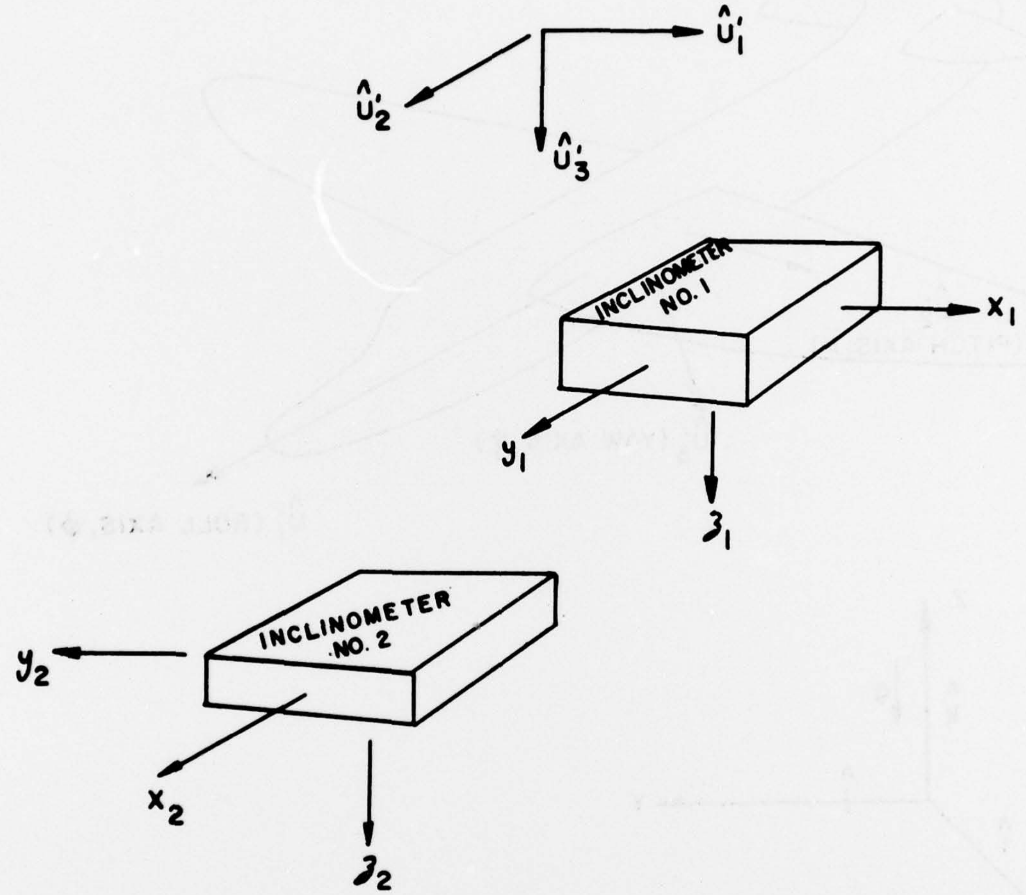


Figure C3. INCLINOMETER COORDINATE SYSTEMS

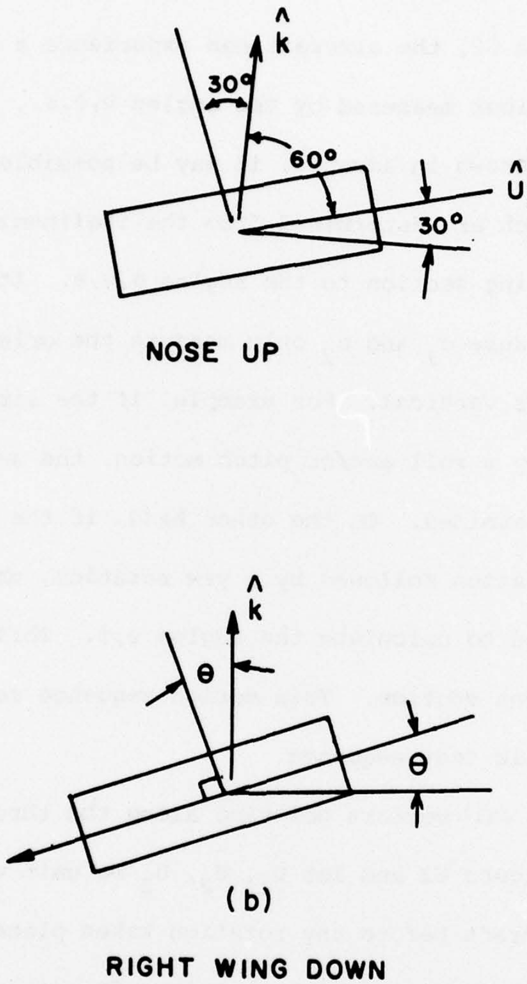


Figure C4. INCLINOMETER CALIBRATION

APPENDIX D

PROCEDURE TO CALCULATE PITCH, ROLL AND YAW ROTATIONS FROM INCLINOMETER READINGS

Referring to Figure C2, the aircraft can experience a series of pitch, roll and yaw motions measured by the angles ν,ϕ,ψ.. If the sequence of motions is known in advance, it may be possible to relate the values of c_1 and c_2 which are determined from the inclinometer readings as described in the preceding section to the angles ϕ,ν,ψ. It is not always possible to do this because c_1 and c_2 only measure the orientation of the aircraft relative to the vertical. For example, if the aircraft experiences a yaw motion followed by a roll and/or pitch motion, the amount of the yaw motion can never be determined. On the other hand, if the aircraft experiences a pitch rotation followed by a yaw rotation, then the values of c_1 and c_2 can be used to calculate the angles ν,ψ. This case will be considered in the present section. This motion sequence corresponds exactly to the cross-axis test sequence.

Let $\hat{U}_{1'},\hat{U}_{2'},\hat{U}_{3'}$ be unit vectors pointing along the three axes of the aircraft as shown in Figure C2 and let $\hat{U}_1$, $\hat{U}_2$, $\hat{U}_3$ be unit vectors aligned with the $\hat{U}_{i'}$ of the aircraft before any rotation takes place. Then $\hat{U}_1,\hat{U}_2,\hat{U}_3$ are fixed vectors with respect to which the aircraft orientation can be measured for any sequence of rotations. Using the relations of Korn and Korn#, each rotation about the body axes of the aircraft can be represented as a matrix. A sequence of roll, pitch, and yaw rotations can be represented as a product of the individual matrices as follows:

#Korn, G.A. and Korn, T.M. "Mathematical Handbook for Scientists and Engineers Engineers", 2nd Edition., McGraw-Hill, 1968. Section 14.10-5.

$$[A] = \begin{bmatrix} \cos\nu\cos\psi & -\cos\nu\sin\psi & \sin\nu \\ \sin\phi\sin\nu\cos\psi + \cos\phi\sin\psi & -\sin\phi\sin\nu\sin\psi + \cos\phi\cos\psi & -\sin\phi\cos\nu \\ -\cos\phi\sin\nu\cos\psi + \sin\phi\sin\psi & \cos\phi\sin\nu\sin\psi + \sin\phi\cos\psi & \cos\phi\cos\nu \end{bmatrix}$$

The unit vectors $\hat{U}_{1'}, \hat{U}_{2'}, \hat{U}_{3'}$ fixed with the aircraft are related to the unit vectors $\hat{U}_1, \hat{U}_2, \hat{U}_3$ fixed in space by

$$\begin{bmatrix} \hat{U}_{1'} \\ \hat{U}_{2'} \\ \hat{U}_{3'} \end{bmatrix} = [A] \begin{bmatrix} \hat{U}_1 \\ \hat{U}_2 \\ \hat{U}_3 \end{bmatrix}$$

In the case of the cross-axis test, the aircraft has zero roll followed by an elevation ν and subsequently experiences a yaw ψ. This case can be obtained simply by setting $\phi=0$ in the matrix A . Thus,

$$[A]_{\substack{\text{cross-axis}\\ \text{test}}} = \begin{bmatrix} \cos\psi & -\sin\psi & \sin\nu \\ \sin\psi & \cos\psi & 0 \\ -\sin\nu\cos\psi & \sin\nu\sin\psi & \cos\nu \end{bmatrix} = [A]_{cat}$$

The unit vectors $\hat{U}_{1'}, \hat{U}_{2'}$ can be written as follows:

$$\hat{U}_{1'} = [A] \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \cos\psi \\ \sin\psi \\ -\sin\nu\cos\psi \end{bmatrix}$$

$$\hat{U}_{2'} = [A] \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} -\sin\psi \\ \cos\psi \\ \sin\nu\sin\psi \end{bmatrix}$$

The values of c_1 and c_2 follow from their definition. Specifically,

$$c_1 = \hat{U}_{1'} \cdot \hat{k} = \hat{U}_{1'} \cdot -\hat{U}_3 = (\cos\psi, \sin\psi, -\sin\nu\cos\psi) \cdot (0,0,1) = \sin\nu\cos\psi$$

$$c_2 = \hat{U}_{2'} \cdot \hat{k} = \hat{U}_{2'} \cdot -\hat{U}_3 = (-\sin\psi, \cos\psi, \sin\nu\sin\psi) \cdot (0,0,-1) = -\sin\nu\sin\psi$$

Using the relations

$$\sin\nu\cos\psi = c_1$$

$$-\sin\nu\sin\psi = c_2$$

one can easily write explicit relations for ν, ψ (the pitch and yaw rotations) in terms of the values of c_1 and c_2 which are determined from the inclinometer data. The relations are:

$$\sin\nu = \sqrt{c_1^2 + c_2^2}\ , \qquad \nu = \arc\sin\sqrt{c_1^2 + c_2^2}$$

$$\cos\psi = c_1 \Big/ \sqrt{c_1^2 + c_2^2}\ , \qquad \psi = \arc\cos c_1 \Big/ \sqrt{c_1^2 + c_2^2}$$

or,

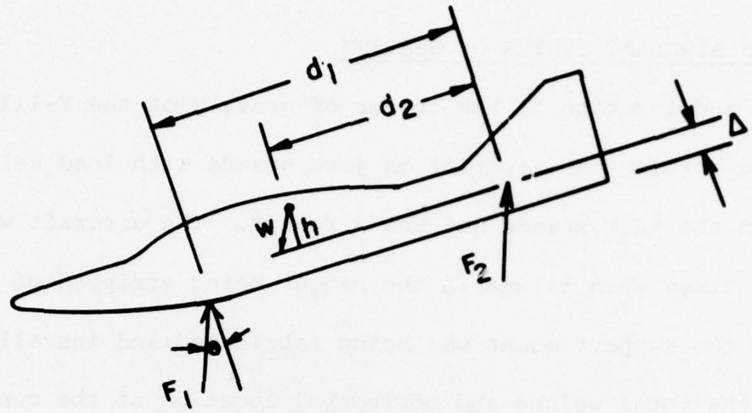
$$\tan\psi = -c_2/c_1\ , \qquad \psi = \arc\tan -c_2/c_1$$

APPENDIX E

DETERMINATION OF AIRCRAFT CENTER OF GRAVITY

The weight and location of the center of gravity of the F-111 was determined by supporting the aircraft on jack stands with load cells inserted between the jack stands and the aircraft. The aircraft was weighed several times when it was in the hangar being stripped of excess weight and when the support mount was being fabricated and installed.

Computing the total weight and horizontal location of the center of gravity was very easy to accomplish; however, determining the vertical location of the center of gravity required using measured data and an analytical procedure. The first step was to support the aircraft on three jacks and to level the aircraft in pitch and roll. The fuselage stations of each jack point were obtained from the aircraft T.O. Also, water line data for each jack point was determined. Load cell readings were taken. The horizontal location of the center of gravity could now be computed. The aircraft was then tilted, nose down, one degree. A Warren-Knight Company model 200-G inclinometer was used to measure the tilt to within 5 minutes of arc. Load cell readings were again taken. The aircraft was then tilted, nose down, two degrees and load cell readings repeated. The aircraft was then tilted tail down one degree, then two degrees, and load cell readings obtained. The following analytical procedure was then used:



d_1 = distance between fore and aft jack points measured along aircraft roll axis.

d_2 = distance between aft jack point and center of gravity measured along aircraft roll axis.

Δ = difference in water lines between fore and aft jack points.

h = height above aft jack point to center of gravity.

θ = angle of tilt.

W = total weight of aircraft.

F_1 = fore load cell force.

F_2 = aft load cell force.

Summing moments about the aft jack point:

$\sum M_2 = 0$ +

$$F_1 \cos\theta d_1 - W\cos\theta d_2 - W\sin\theta h - F_1 \sin\theta\, \Delta = 0$$

Everything in the above equation is known except h.

Using the above procedure, the final results were obtained:

Total weight: 26,506 lbs.

Horizontal locations:	F.S. 543	wings forward
	F.S. 558	wings retracted
Vertical location:	44.89 inches above the lower skin.	

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Title: F-111 Positional Error Analysis When Mounted on 3 Axis Positioner
at RADC Newport Test Annex
Date: October 1977

Please make the following corrections:

1. Cover - Add the name "Dr. Richard W. Perkins" as co-author.

2. DD Form 1473 - Add the name "Dr. Richard W. Perkins" in Block 7.

3. Page 18, 1st paragraph - In the last sentence, "s" should be "S".

4. Page 18, 2nd paragraph - In the second sentence, capitalize the first word "An".

5. Page 28, paragraph 3. - In the second sentence, the word "inclinomete" should read "inclinometer".

6. Page 31, Figure 2, NOTE - Insert the word "alignment" between the words aximuth and effects.

7. Page 34, Figure 5 - In the title, insert the word "readout" between synchro and the word and.

8. Page 40, Table 3, Note 1 - Add the greek symbol ϕ after the first sin and the symbol ν after the second sin.

9. Page 40, Table 3, Note 1 - 0.0001 should read 0.001.

10. Page 41, Table 4 - 10 December 1976 date should be changed to 10 December 1975.

11. Page 46, Table 8, Note 1 - Add the greek symbol ϕ after the first sin and the symbol ν after the second sin.

12. Page 46, Table 8, Note 1 - 0.0001 should read 0.001 in both places.

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